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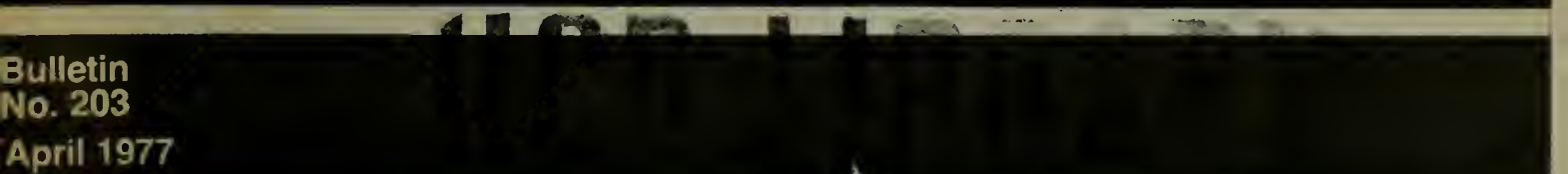
Performance of the Oroville Dam and Related Facilities During the August 1, 1975 Earthquake



Bulletin
No. 203
April 1977

Photo on Cover —
Is of Lake Oroville and Oroville Dam

Department of
Water Resources

Bulletin No. 203

Performance of the Oroville Dam and Related Facilities During the August 1, 1975 Earthquake

April 1977

Claire T. Dedrick
Secretary for Resources

Edmund G. Brown Jr.
Governor

Ronald B. Robie
Director

The Resources
Agency

State of
California

Department of
Water Resources

FOREWORD

On August 1, 1975 at 1:20 p.m., an earthquake of Richter Scale Magnitude 5.7 occurred about 12 kilometres (7.5 miles) southwest of Oroville Dam, a principal feature of the California State Water Project. During the main quake and the many aftershocks that followed, the Oroville complex continued operation virtually without interruption.

Inspection began during the foreshocks; immediately following the main shock, the Department of Water Resources began detailed inspections of the Oroville facilities and found that only minor damage had occurred. Service from the two power plants of the Oroville complex -- Edward Hyatt and Thermalito Powerplants -- was interrupted for only about 45 minutes.

On August 8, the Department of Water Resources convened its Consulting Board for Earthquake Analysis to review the post-earthquake situation. Then, in September, under the guidance of the Special Consulting Board for the Oroville Earthquake, the Department began detailed studies and investigations of the August 1 event.

Bulletin No. 203 documents the performance of Oroville Dam and related facilities during the August 1 earthquake, the sequence of aftershocks that followed during the remainder of August, and the scattered shocks that continued during the fall months. The bulletin is presented in two parts.

In Part 1, the performance of the Oroville complex during the main event and succeeding aftershocks is described. Also included is a discussion of the detailed inspections and investigations of the Oroville facilities that followed the August 1 event. Part 1 also contains discussions of the seismology and geologic history of the affected area, along with seismological and geological data from investigations conducted before and after the earthquake.

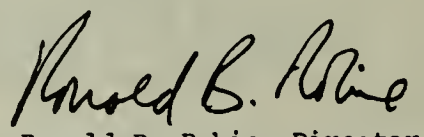
Part 1 has been reviewed by the Special Consulting Board for the Oroville Earthquake.

Part 2 describes the actions of the Department of Water Resources in carrying out its responsibilities for the safety of all dams in the area affected by the earthquake. As specified in Division 3 of the California Water Code, the Department, through its Division of Safety of Dams, has jurisdiction over (1) all California dams (except federal dams) 7.6 metres (25 feet) high or more that impound more than 18 500 cubic metres (15 acre-feet) of water, and (2) dams more than 1.8 metres 6 feet) high that impound at least 62 000 cubic metres (50 acre-feet).

Part 2 discusses the actions of the Division of Safety of Dams following the August 1 event, including its evaluation of the safety and

performance of all jurisdictional dams in the Oroville area. Also discussed are studies of the seismicity of the Oroville area. Finally, Part 2 presents a discussion of the effect of the Oroville earthquake on seismic criteria that should be used as a basis for (1) the design of new dams, and (2) evaluations of the adequacy of existing dams and related facilities.

A subsequent report will be prepared that will include structural reanalysis of the Oroville Project facilities for a larger earthquake, and results of the seismological and geological investigations.



Ronald B. Robie, Director
Department of Water Resources
The Resources Agency
State of California

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The contribution of data by the United States Geological Survey, Woodward-Clyde Consultants and the University of California, Berkeley, is acknowledged.

* University of California, Berkeley

CONVERSION FACTORS

English to Metric System of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)	25.4	millimetres (mm)
		.0254	metres (m)
	feet (ft)	.3048	metres (m)
	miles (mi)	1.6093	kilometres (km)
Area	square inches (in^2)	6.4516×10^{-4}	square metres (m^2)
	square feet (ft^2)	.092903	square metres (m^2)
	acres	4046.9	square metres (m^2)
		.40469	hectares (ha)
		.40469	square hectometres (hm^2)
		.0040469	square kilometres (km^2)
	square miles (mi^2)	2.590	square kilometres (km^2)
Volume	gallons (gal)	3.7854	litres (l)
		.0037854	cubic metres (m^3)
	million gallons (10^6 gal)	3785.4	cubic metres (m^3)
	cubic feet (ft^3)	.028317	cubic metres (m^3)
	cubic yards (yd^3)	.76455	cubic metres (m^3)
	acre-feet (ac-ft)	1233.5	cubic metres (m^3)
		.0012335	cubic hectometres (hm^3)
		1.233×10^{-6}	cubic kilometres (km^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
		.028317	cubic metres per second (m^3/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
		6.309×10^{-5}	cubic metres per second (m^3/s)
	million gallons per day (mgd)	.043813	cubic metres per second (m^3/s)
Mass	pounds (lb)	.45359	kilograms (kg)
	tons (short, 2,000 lb)	.90718	tonne (t)
		907.18	kilograms (kg)
Power	horsepower (hp)	0.7460	kilowatts (kW)
Pressure	pounds per square inch (psi)	6894.8	pascal (Pa)
Temperature	Degrees Fahrenheit (°F)	$\frac{tF - 32}{1.8} = tC$	Degrees Celsius (°C)

Figure 1. Aerial View of the Oroville Facilities and Epicentral Area

PART I

Chapter I. INTRODUCTION

Oroville Dam is situated in the foothills of the Sierra Nevada above the Sacramento Valley. The dam is 8 kilometres (5 miles) east of the city of Oroville and about 209 kilometres (130 miles) northeast of San Francisco.

On August 1, 1975 at 1320 hours (1:20 p.m.) PDT, an earthquake of Richter Scale Magnitude 5.7 occurred about 12 kilometres (7.5 miles) southwest of Oroville Dam.[1/] During the main event and the many aftershocks that followed, the Oroville facilities continued operating without interruption except for about 45 minutes of power generation. Minor damage observed at some of the facilities was repaired under routine maintenance procedures.

The Oroville earthquake series began with a number of foreshocks on June 28, 1975. Then, on August 1, twenty-nine foreshocks occurred within 5 hours of the main shock. The largest of these had a magnitude of 4.8. Many aftershocks, the largest of which had a magnitude of 5.1, occurred throughout August, and scattered shocks continued.

Description of the Oroville Facilities

Oroville Dam and its appurtenances, along with the Thermalito facilities (Figures 1 and 2), comprise a multiple purpose project, which includes water conservation, power generation, flood control, recreation, and fish and wildlife enhancement. The lake stores winter and spring runoff, which is released into the Feather River as necessary to supply project needs and commitments. The pumped-storage capability of the Oroville facilities permits maximum use of the value of power produced by these releases.

Water releases from Edward Hyatt Powerplant are diverted from the Feather River at the Thermalito Diversion Dam, a concrete gravity structure with a radial gated crest section. These releases pass through the Thermalito Power Canal and Thermalito Forebay, through Thermalito Powerplant, and into Thermalito Afterbay. The Thermalito Diversion Pool, Power Canal, and Forebay have a common water surface to accommodate flow reversals for the pumped-storage operation. Thermalito Afterbay stores the plant discharges for the pumped-storage or conventional operation and reregulates flow for uniform return to the Feather River.

Migrating salmon and steelhead blocked by the Oroville Complex are diverted from the river into the Feather River Fish Hatchery at the Fish Barrier Dam, located 0.8 kilometre (0.5 mile) downstream of Thermalito Diversion Dam.

The Investigating Organization

On August 8, 1975, the Department of Water Resources convened its Consulting

---

1/ *In 1935 C. R. Richter reported a method for classifying the size of earthquakes which was based on the maximum amplitude recorded by a Wood-Anderson seismograph corrected to an epicentral distance of 100 kilometres. An earthquake with a Richter Scale Magnitude of 2.0 would scarcely be noticed. A quake with tude of 5.0 or less rarely causes significant damage.*

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or Earthquake Analysis to review
neral post-earthquake situation
and e preliminary data assembled.
On September 11 and 12, 1975, a Special Consulting Board, composed of the Board for Earthquake Analysis and other consultants in the field of design and construction of dam and reservoir projects, reviewed the Department's programs for data collection and evaluation of structural seismic safety.

The Special Consulting Board for the Oroville Earthquake consisted of the following members:

George W. Housner, Chairman, California Institute of Technology

Clarence R. Allen, California Institute of Technology

Bruce A. Bolt, University of California, Berkeley

Thomas M. Leps, Consultant

Philip C. Rutledge, Mueser, Rutledge, Wentworth and Johnston

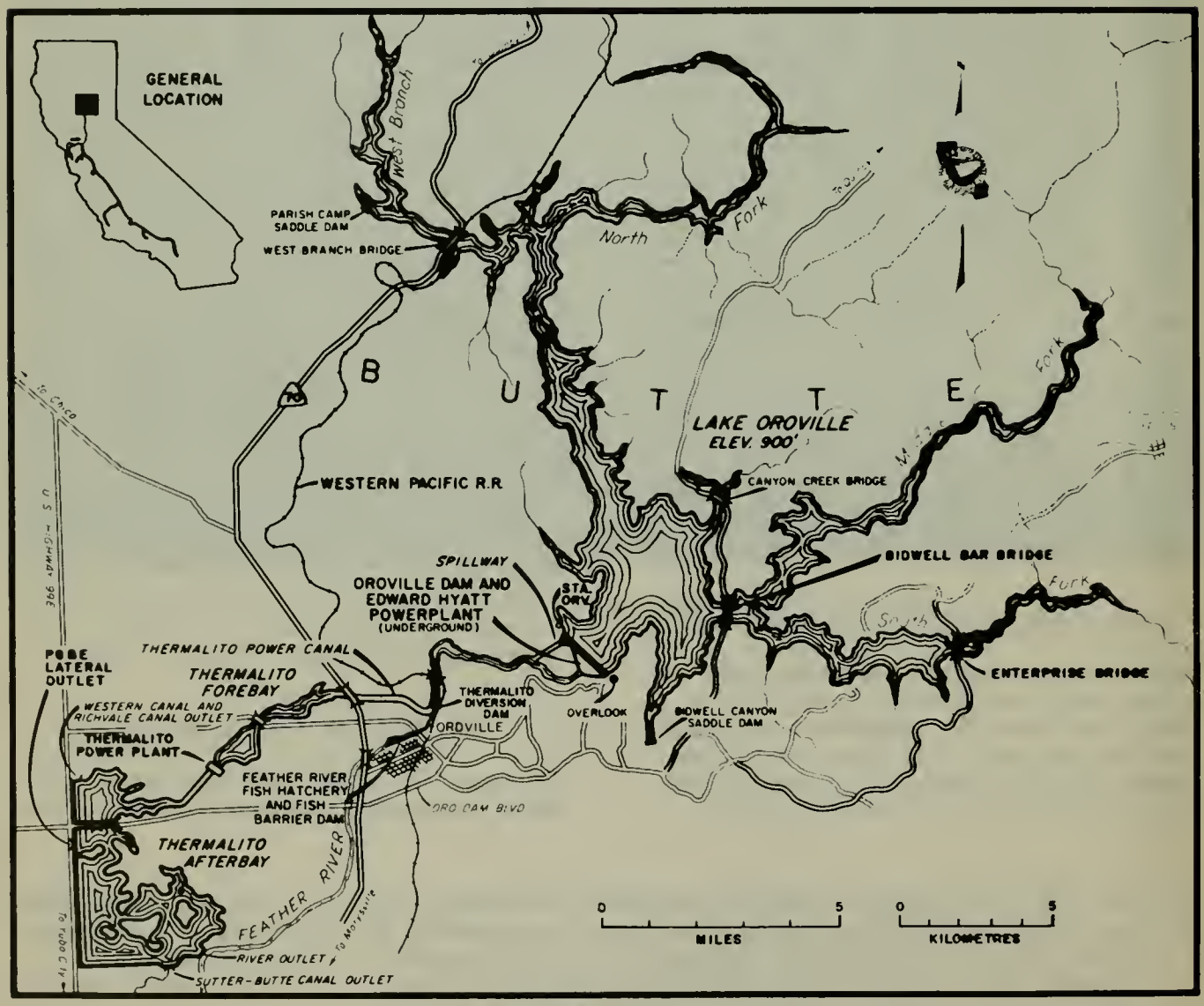


Figure 2. Location Map -- Oroville Facilities

John A. Blume, John A. Blume and Associates

Wallace L. Chadwick, Consultant

Alan L. O'Neill, Consultant

H. Bolton Seed, University of California, Berkeley

With the general guidance of the Special Consulting Board, several earthquake-related investigations were undertaken. These include (1) geologic studies and mapping of the epicentral area and the causative fault, (2) seismological studies dealing with the earthquake sequence and fault plane resolution, (3) determination of the seismic safety of project structures under loading of the maximum credible earthquake for this area, (4) surveys of the area, and (5) an evaluation of the existing seismic instrumentation system. Most of these studies are still in progress.

The performance of the Oroville facilities during the height of seismic activity and the following months is presented in Chapter II. Chapter III is an evaluation of the seismic activity during this period, and geologic investigations are presented in Chapter IV.

Chapter II. PERFORMANCE OF PROJECT FACILITIES

Conclusions

Only minor superficial damage was sustained by the Oroville facilities during the August 1, earthquake. The inspections and instrumentation data show that all facilities are structurally sound.

Oroville Facilities Damage

The following is a listing of the damage and estimated cost of repairs:

Damage	Estimated Cost
Oroville Dam Spillway Chute	
Chute wall joint spalling at terminal structure	No repair required
Operation and Maintenance Center	
Building damage (plaster cracking, etc., nonstructural)	$2,500
Thermalito Powerhouse Structure	
Wall cracking (nonstructural)	$ 180
Thermalito Tail Channel	
Rock slope protection failure - perhaps 5% of the slope area is involved. Repair to original considered costly. Redesign and reconstruction probably required.	NA
Thermalito Afterbay River Outlet Embankments	
Settlement and cracking of non-compacted embankments	$4,500

Operation of Edward Hyatt and Thermalito Powerplants

During the main event earthquake, Hyatt and Thermalito Powerplants were generating at maximum capacity. At 1321 hours, (1.21 p.m.) three Hyatt units and all four Thermalito units automatically disconnected, and at 1324

hours (1:24 p.m.) the other three Hyatt units disconnected.

Within 45 minutes, four of the Hyatt units and all the Thermalito units were restarted. Discoloration of the tailwater from Hyatt Powerplant was noticed. The plant and intake structure were inspected for damage and none was found. The tailwater returned to normal within a short time. Discoloration was also observed in the Palermo Canal during the same period. The other two Hyatt units were restarted later as the power system stabilized. The discoloration of the tailwater was due to depositions in the outlet works being disturbed by the seismic activity.

Oroville Dam

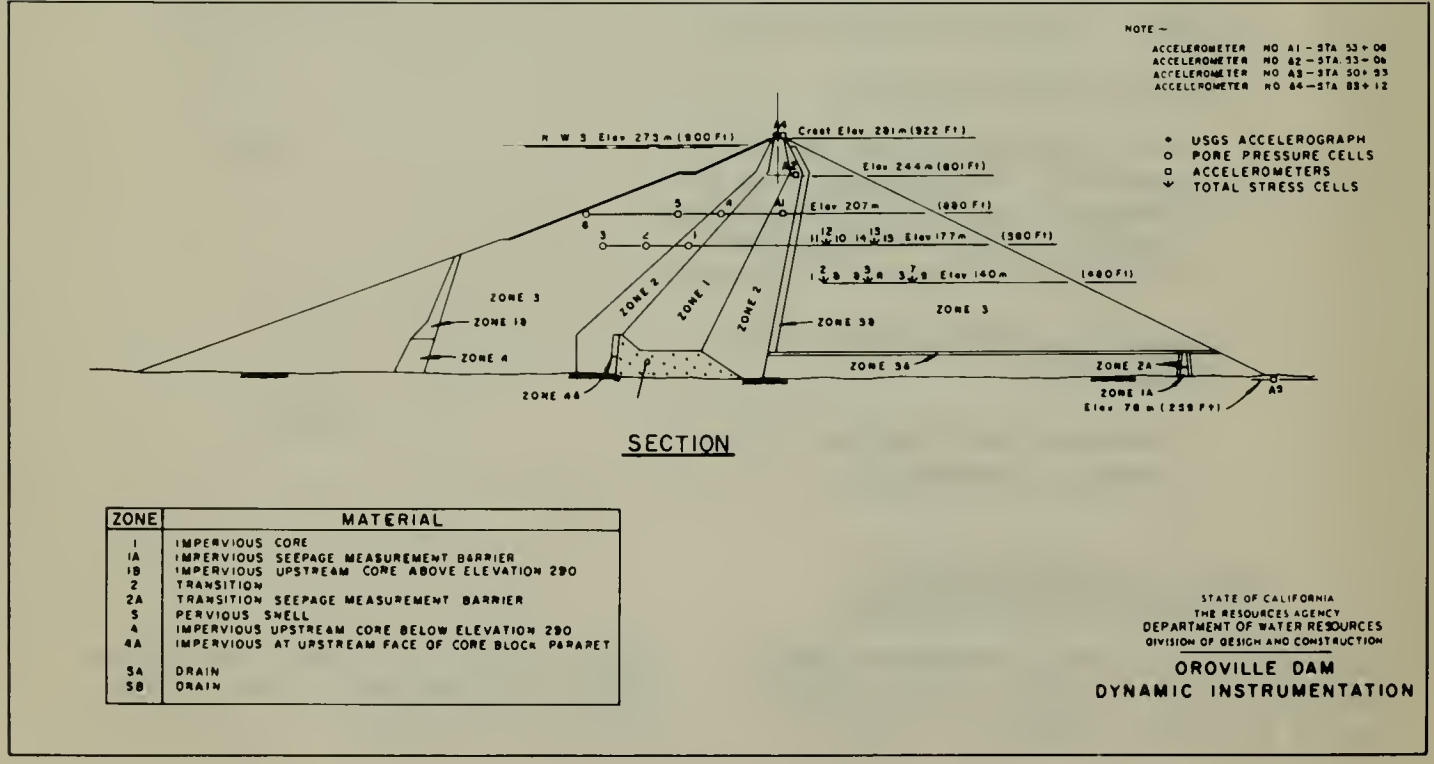
Lake Oroville was filled to an elevation of 273 metres (897.5 feet) on June 24, 1975. Drawdown of the reservoir started immediately thereafter because of released for downstream needs.

Special inspections of the facilities commenced after the magnitude 3.8 foreshock which occurred at 0845 (8:45 a.m.) PDT, August 1, 1975, and were increased after the main event at 1320 (1:20 p.m.) PDT.

Inspections and more frequent reading of instruments continued throughout the intense aftershock period. Inspections covered all internal galleries and accessible tunnels; the dam slopes, crest groins, and abutment areas; and adjacent structures.

Accelerometers

Acceleration data were provided by four accelerometers (Figure 3) (force-balance type) installed in, or immediately adjacent to, Oroville Dam and by three U. S. Geological Survey (USGS) - DWR cooperative program strong-motion accelerographs located in the grout gallery, on the crest, and at the sensitive seismograph station ORV northwest of the dam. During the August 1 earthquake, the instrument in the grout gallery was inoperable because of a disconnected wire that was found and corrected that day. All others



SECTION

ZONE	MATERIAL
1	IMPERVIOUS CORE
1A	IMPERVIOUS SEEPAGE MEASUREMENT BARRIER
1B	IMPERVIOUS UPSTREAM CORE ABOVE ELEVATION 290
2	TRANSITION
2A	TRANSITION SEEPAGE MEASUREMENT BARRIER
3	PERVIOUS SHELL
4	IMPERVIOUS UPSTREAM CORE BELOW ELEVATION 290
4A	IMPERVIOUS AT UPSTREAM FACE OF CORE BLOCK PARAPET
5A	DRAIN
5B	DRAIN

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF DESIGN AND CONSTRUCTION

OROVILLE DAM
DYNAMIC INSTRUMENTATION

Figure 3. Dynamic Instrumentation

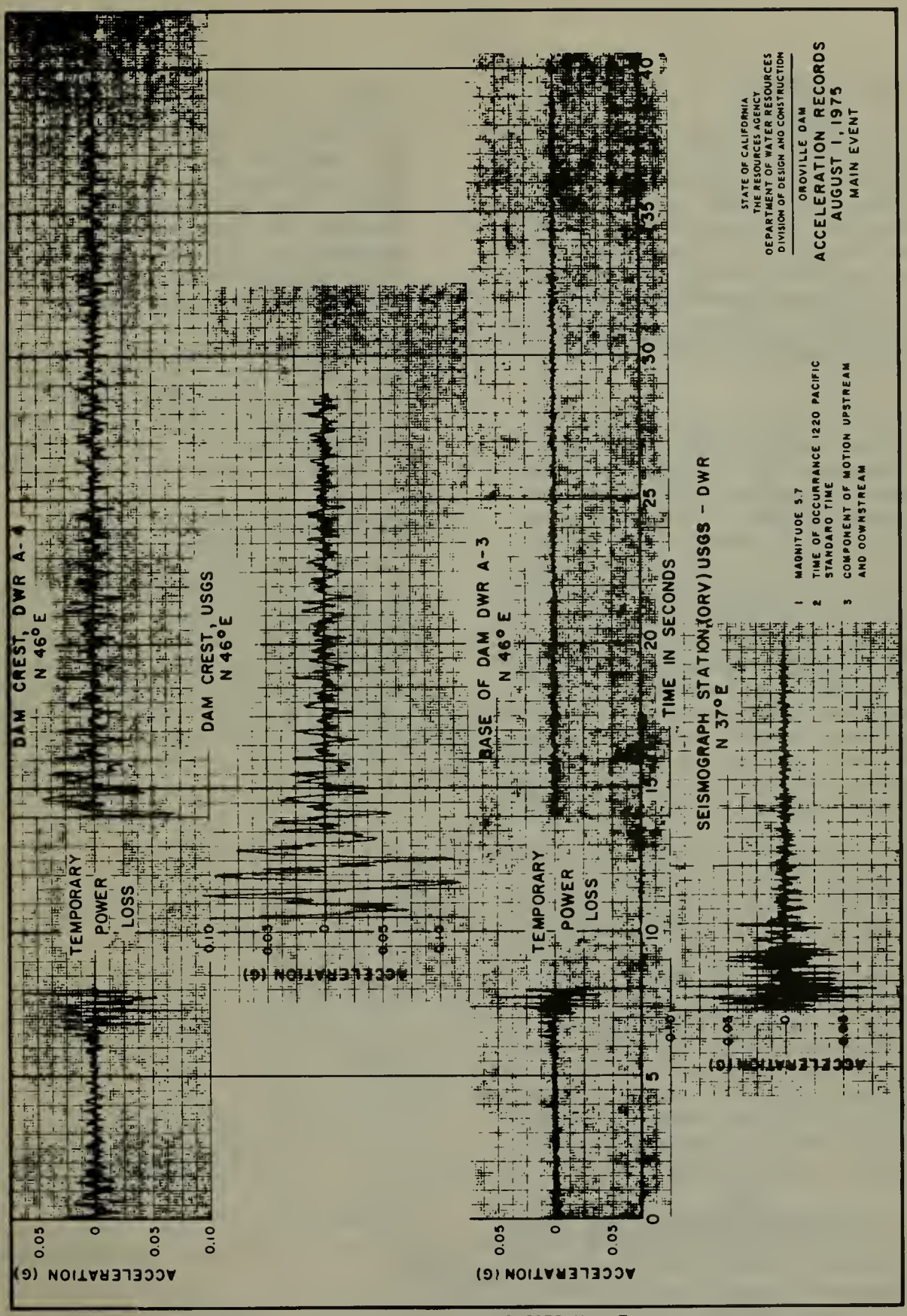


Figure 4. Acceleration Records August 1, 1975, Main Event

provided acceleration recordings.

During the main event, records of the four accelerometers were interrupted by a malfunction of the standby power switching equipment, which occurred during the interval of high acceleration (Figure 4). This equipment was immediately repaired. The recorders are activated by an acceleration of 0.01 g on the vertical transducer of the accelerometer at the base of the dam (A-3).

During the main shock, maximum recorded acceleration at the base of the dam was 0.09 g in the upstream-downstream and vertical directions, compared with 0.13 g transverse to the river. However, higher values may have occurred during the period for which the record is missing. Two of the many aftershocks produced peak recorded accelerations of 0.08 g and 0.09 g upstream-downstream. Vertical and cross-river components were not decipherable for these two aftershocks. All other recorded acceleration peaks were less than 0.05 g, with different components being the highest in the different events.

The acceleration records for the main event for the two crest instruments, the base, and station ORV, are shown in Figure 4. In general, accelerations during the main shock measured at the dam base are smaller than those recorded by the USGS-DWR strong-motion instrument located at the seismograph station ORV (note that the two instruments do not measure in the same direction). A comparison between the two crest instruments shows that the USGS-DWR instrument measured slightly higher accelerations.

An interesting factor brought out by examination of the aftershock records is the amplification of acceleration between A-4 (crest) and A-3 (base). This is illustrated in Figure 5, which is a plot of the ratio of peak accelerations measured at A-4 and A-3, versus the peak acceleration measured at A-3, for the component of motion parallel to the river. It shows that the amplification depends heavily on the magnitude of input acceleration (A-3). This relationship has been observed in other instances and can be explained as follows: With larger base input motion, there is an increase in embankment strain and damping.

The other two directional components indicate similar amplification patterns but these are not as pronounced. Generally, amplification at the embedded accelerometers, A-1 and A-2, was not as great and more exceptions occurred.

Dynamic Pore Pressure Cells

Dynamic pore pressure cells are located in the upstream transition and Shell Zones 2 and 2 (Figure 3). The system is activated and data recorded when acceleration of about 2-percent gravity is exceeded at Accelerometer A-3, which is roughly a shock of magnitude 4.0 to 4.5 within approximately 12 kilometres (7.5 miles) of the dam.

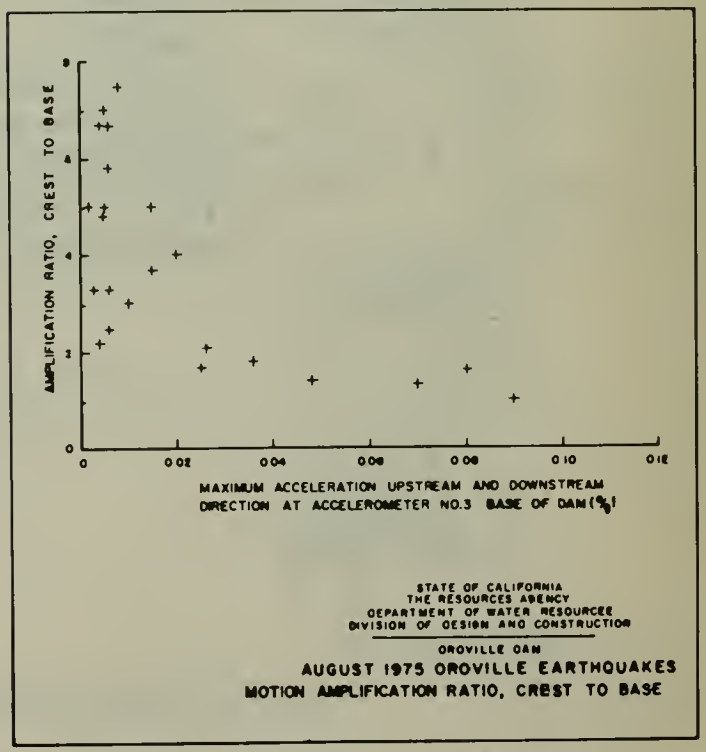


Figure 5. Motion Amplification, Crest to Base

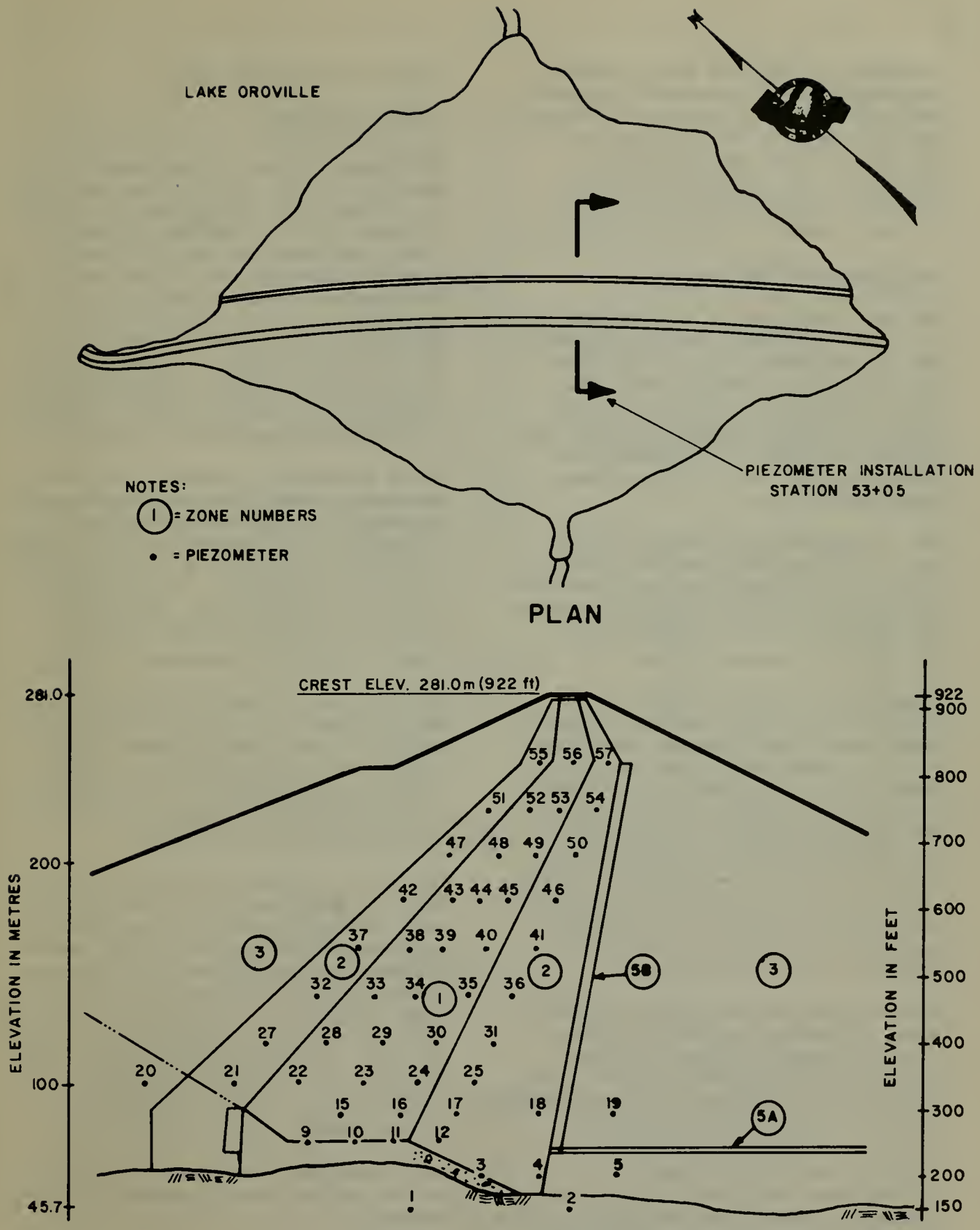


Figure 6. Location of Piezometers

ordings of dynamic pore pressures ere made during 19 events. The maximum response, 82.6 kilopascals (12 psi), was recorded for Cell No. 1 during the main event. This cell also responded most frequently. Local material gradation may be a factor in cell response.

Embankment Soil Stress Cells

The soil stress cells are located in the downstream Shell Zone 3 (Figure 3). The 3-inch diameter cells are placed in five groups of three each. One cell is placed horizontally and measures vertical stresses; the other two measure stresses at 45 degrees from horizontal upstream and downstream, respectively.

Two transducers are located in each cell. One measures both static and dynamic stress; and the other measures static stress only. These instruments are triggered in the same manner as are the pore pressure cells.

Recordings of dynamic stress were obtained during nine events, but only those events that exceeded magnitudes of 5.0 provided meaningful results. Both static and dynamic stresses were the greatest in the vertical direction. The maximum dynamic component, 151.5 kilopascals (22 psi), occurred during the main event. Consistency of direction for the dynamic stress components was found for the three events with magnitude of 5.0 or greater and for respective cell orientation.

Static stress readings remained constant throughout the period of seismicity. Static vertical stresses measured at the dam were within $\pm$ 10 percent of the values determined by the static finite element method analysis. However, measured values from the instruments sloped at 45 degrees were consistently lower than calculated values, and probably resulted from difficulty of obtaining as good embankment contact on both sides of the sloping cells.

Static Piezometers

Fifty-seven hydraulic piezometers were installed in the Oroville Dam and foundation (Figure 6). Piezometer P-1 located in foundation rock beneath the core block, has been indicating a small response to fluctuations of the lake. The earthquakes caused a pressure rise of approximately 4.2 metres (14 feet). The peak pressure, however, remained well below historic values. Piezometer P-2 recorded no appreciable pressure rise from reservoir loading since it measures the downstream seepage pool pressure.

Of the piezometers placed in pervious embankment zones, only one registered a pressure rise from the earthquakes. Piezometer P-32, located in the upstream transition, registered a total rise of 12.1 metres (40 feet). The assumption is that the gradation of the material surrounding this instrument permits a pressure rise to be sustained.

The pressures in the core (Zone 1) have generally reflected the loading of the lake as it goes through annual fluctuations. The low and high peaks have also generally dropped a few feet each year, indicating dissipation of pressures developed during construction.

Increases in pressure within the core (Zone 1) subsequent to the main seismic event varied from zero to a maximum of 16.5 metres (54 feet) of water. Representative seismic response for the core piezometers at different elevations is shown on Figure 7. The largest increases generally occurred in mid-elevation of the core. Even though this rise is substantial, none of the pressures exceeded values recorded during the previous period of high reservoir stage.

The piezometers downstream of the core in the pervious zones remained at zero pressure.

The maximum pressure increase occurred

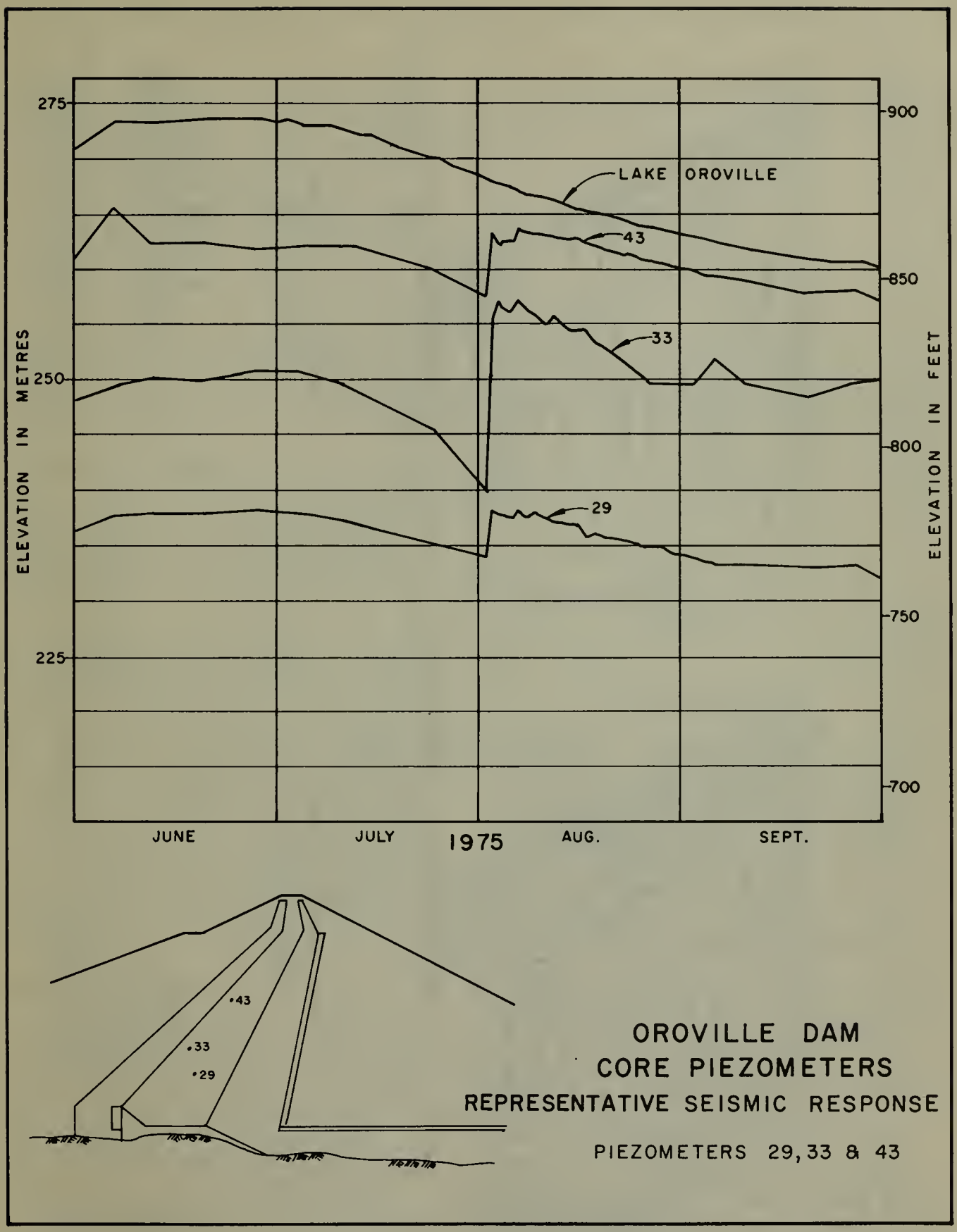


Figure 7. Core Piezometers - Typicol Seismic Response

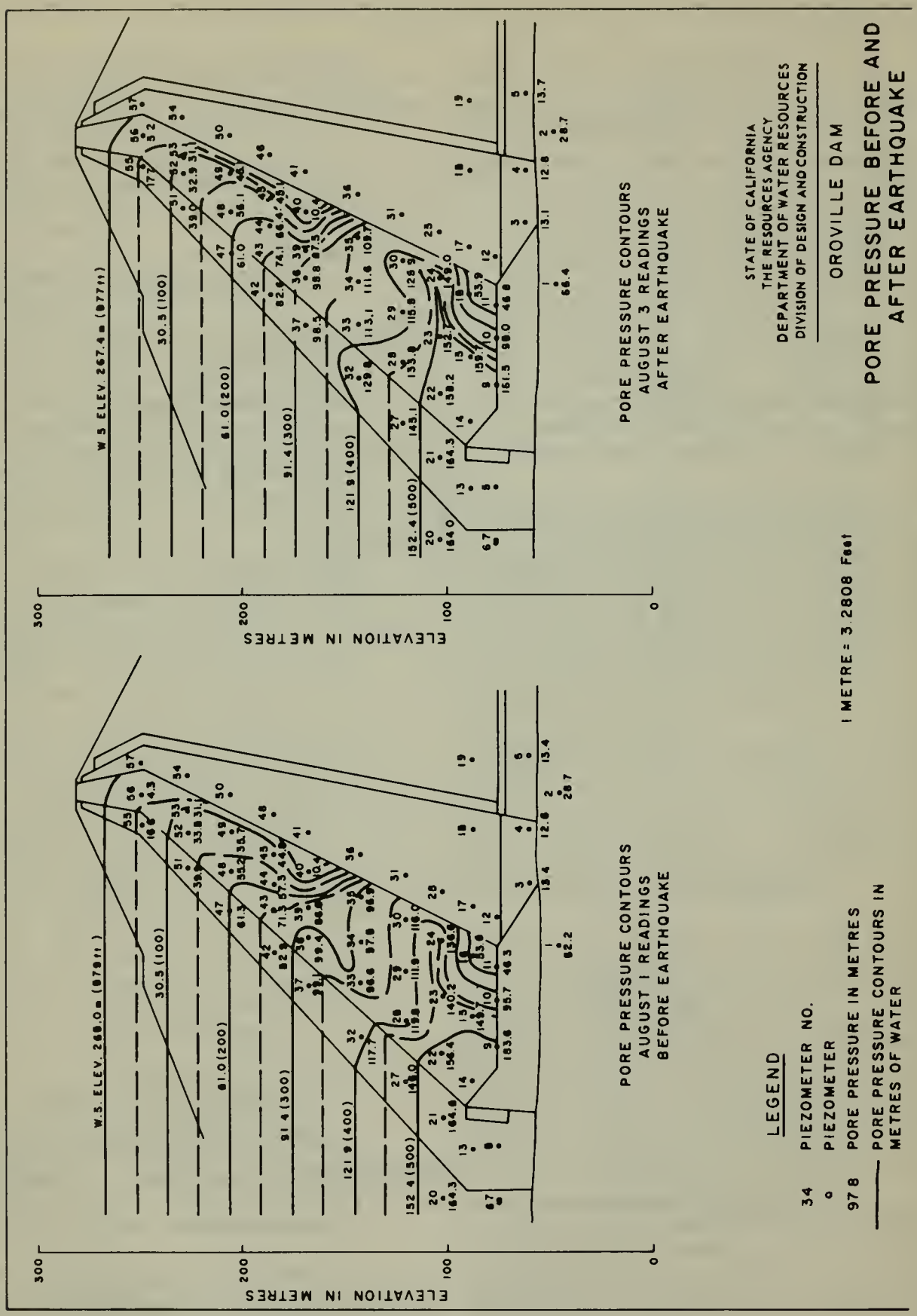


Figure 8. Pore Pressure Contours Before and After Earthquake

during the main shock. The peak was reached on August 3, after which the number and magnitude of the shocks decreased. The pore pressure patterns for August 1 and August 3, before the main earthquake and at peak pressure, are shown on Figure 8. A second peak occurred on August 6, resulting from the magnitude 4.7 aftershock on August 5.

Through December 1975, continued lowering of the lake level and the dissipation of some of the pressure induced by the earthquake caused pore pressures to drop.

Drainage Measurements

The earthquake caused no change in the seepage flow rate at the downstream toe weir. The flow remained approximately 50 litres (14 gallons) per minute (Figure 9).

Drainage from the core block increased from approximately 305 litres (80 gallons) per minute before August 1 to 335 litres (89 gallons) per minute after August 2, and up to 345 litres (91 gallons) per minute after August 14. Most of this change is attributed to increases in seepage from the grout gallery drain holes on the right side of the dam. The change in drainage from core block drain holes was negligible. By the end of September, the seepage rate had reduced to 326 litres (86 gallons) per minute. (Figure 9).

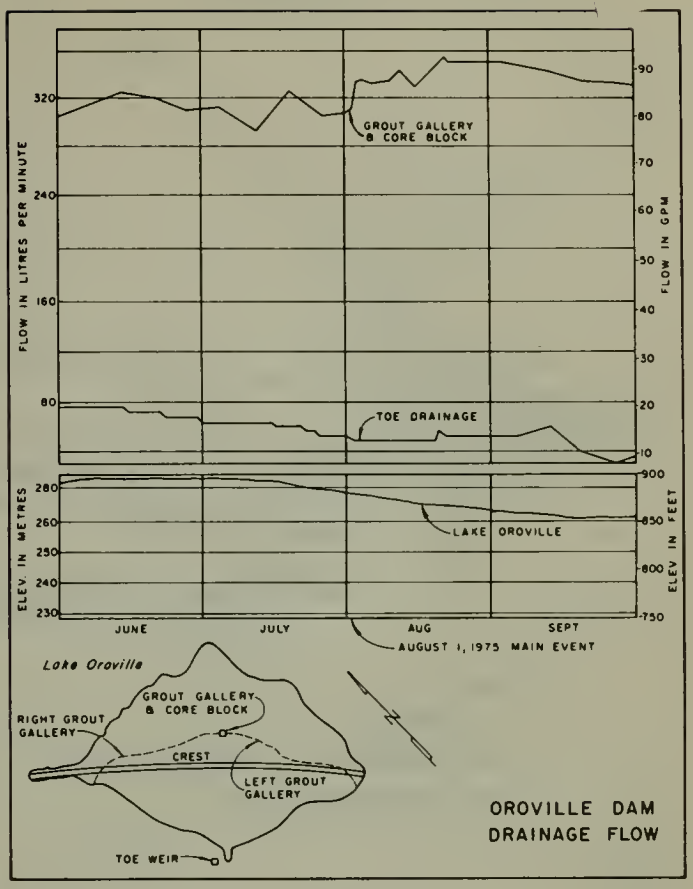


Figure 9. Drainage Flows

Embankment Settlement

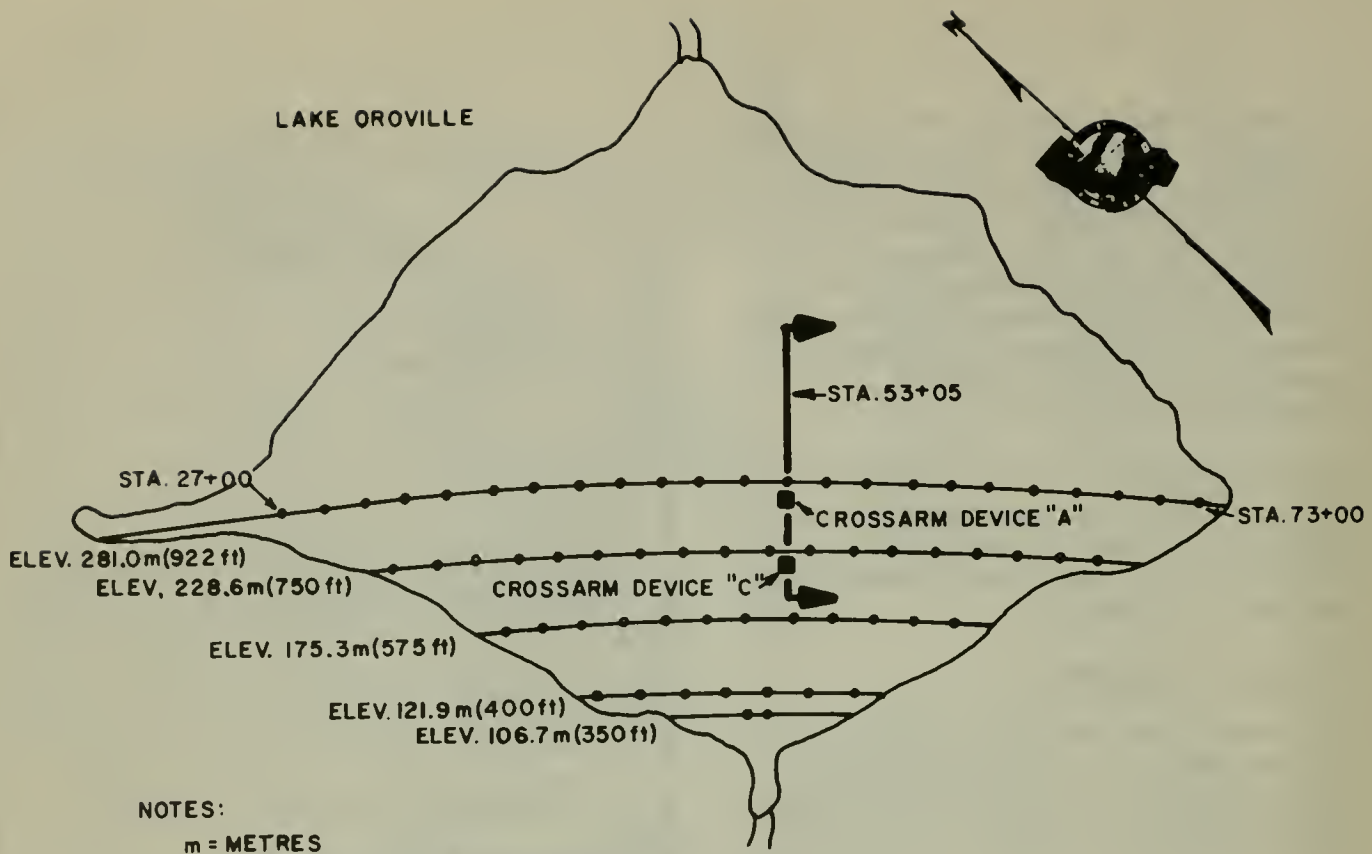
The internal settlement, as measured at the top of Crossarm A (Figure 10) between June 11, 1975 and August 5, 1975, was 15 millimetres (0.05 foot). This is almost the same settlement measured during the previous year June 25, 1974, and June 11, 1975 (Figure 11). Most of the settlement occurred in the lower one-third of the embankment.

The maximum crest settlement, as measured by surveys, was approximately 10 millimetres (0.03 foot). (July 18 to August 12, 1975). Normal settlement at that point in the same period would have been about 2 millimetres (0.006 foot). The surface settlement profiles are shown on Figure 12.

Horizontal Movement of the Embankment

Internal horizontal movements were relatively insignificant. The maximum measured change after the earthquakes was less than 25 millimetres (0.08 foot), a rate that generally agrees with the pattern of movement since installation.

Most of the horizontal movement measured at the crest monuments between July 9, 1975 and August 9, 1975 showed upstream movement up to a maximum of 15 millimetres (0.05 foot) at Station 51. All but one monument at elevation 228.9 metres (751 feet) showed downstream



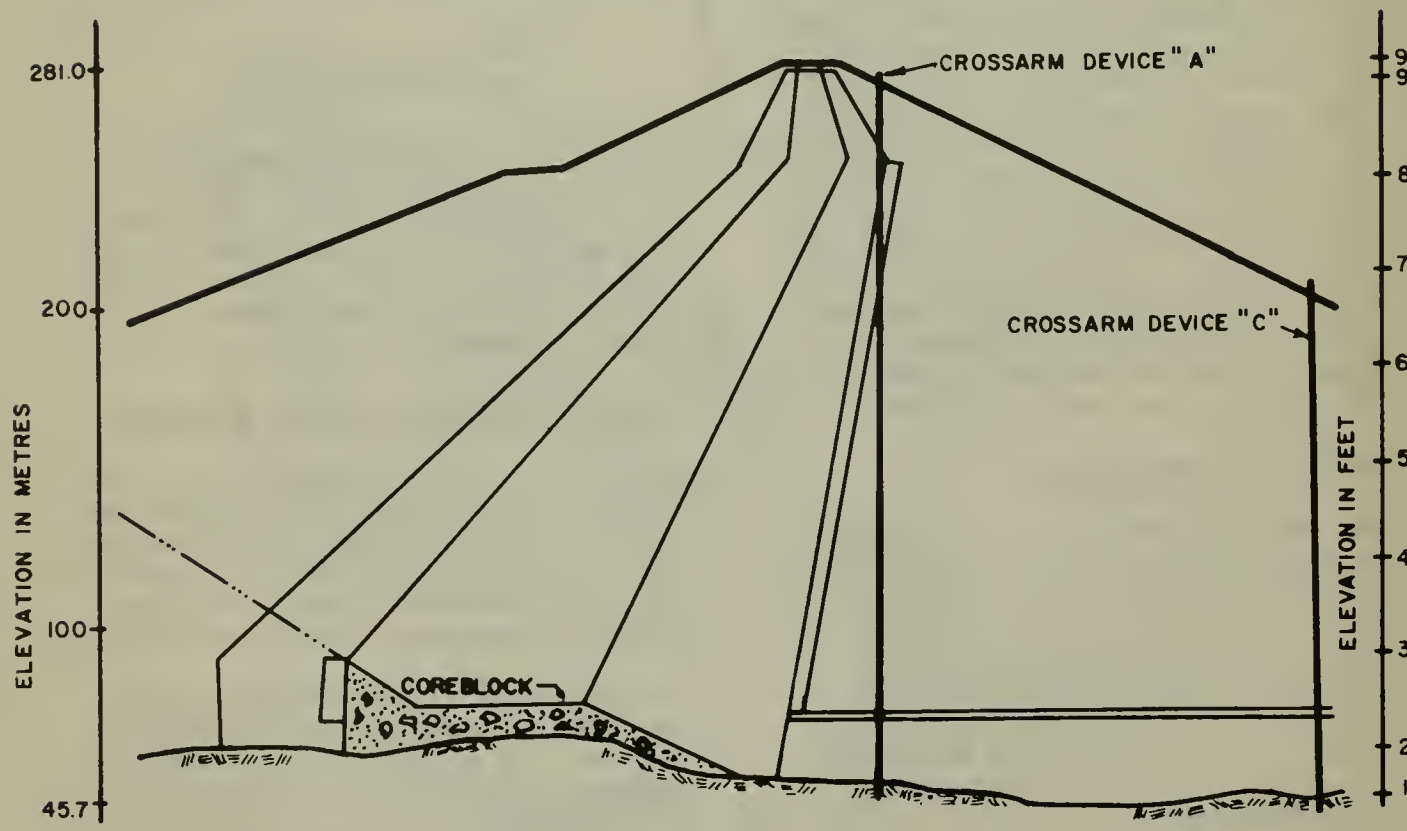


Figure 10. Location of Settlement Devices

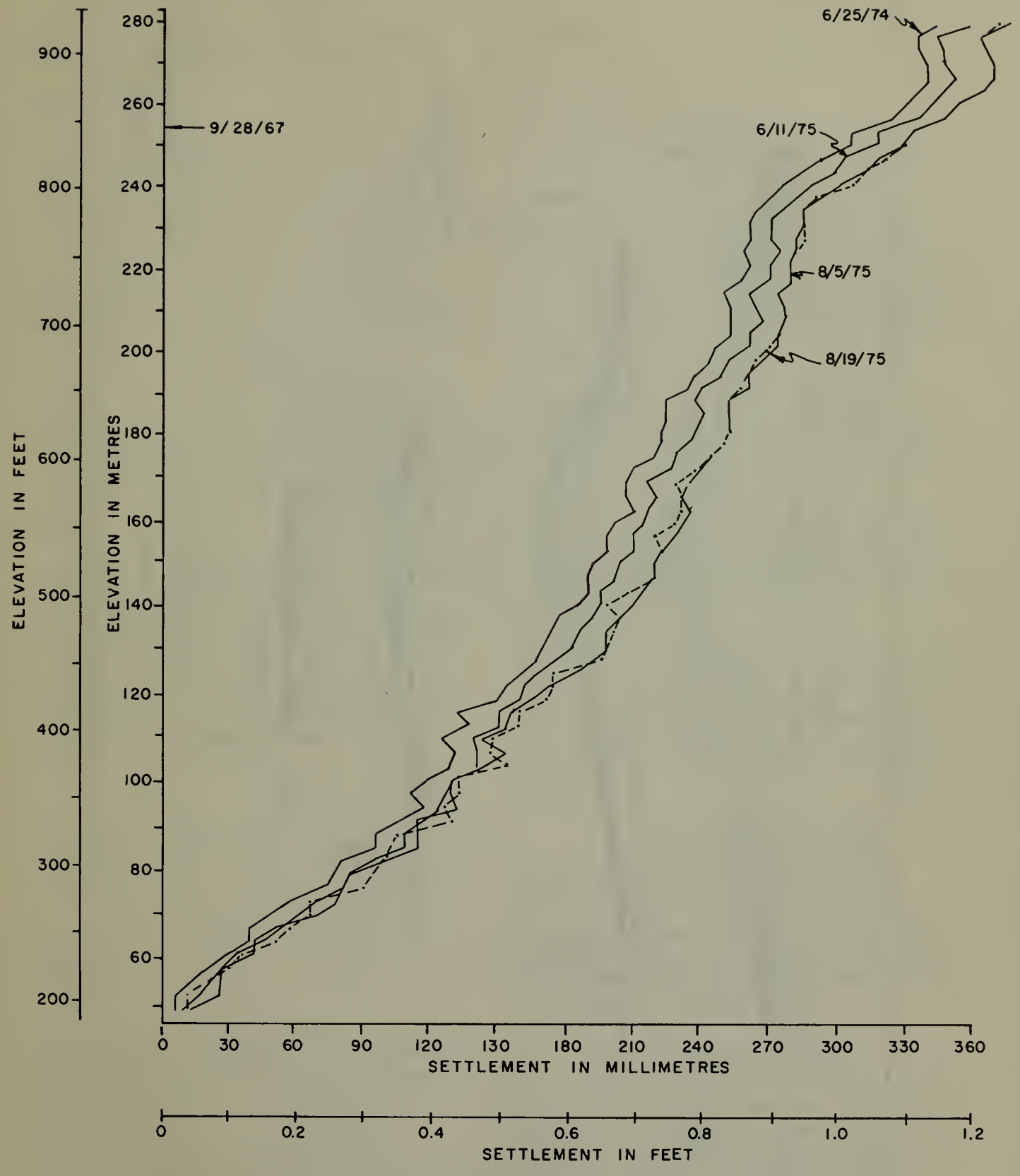


Figure 11. Internal Settlement - Crassarm A

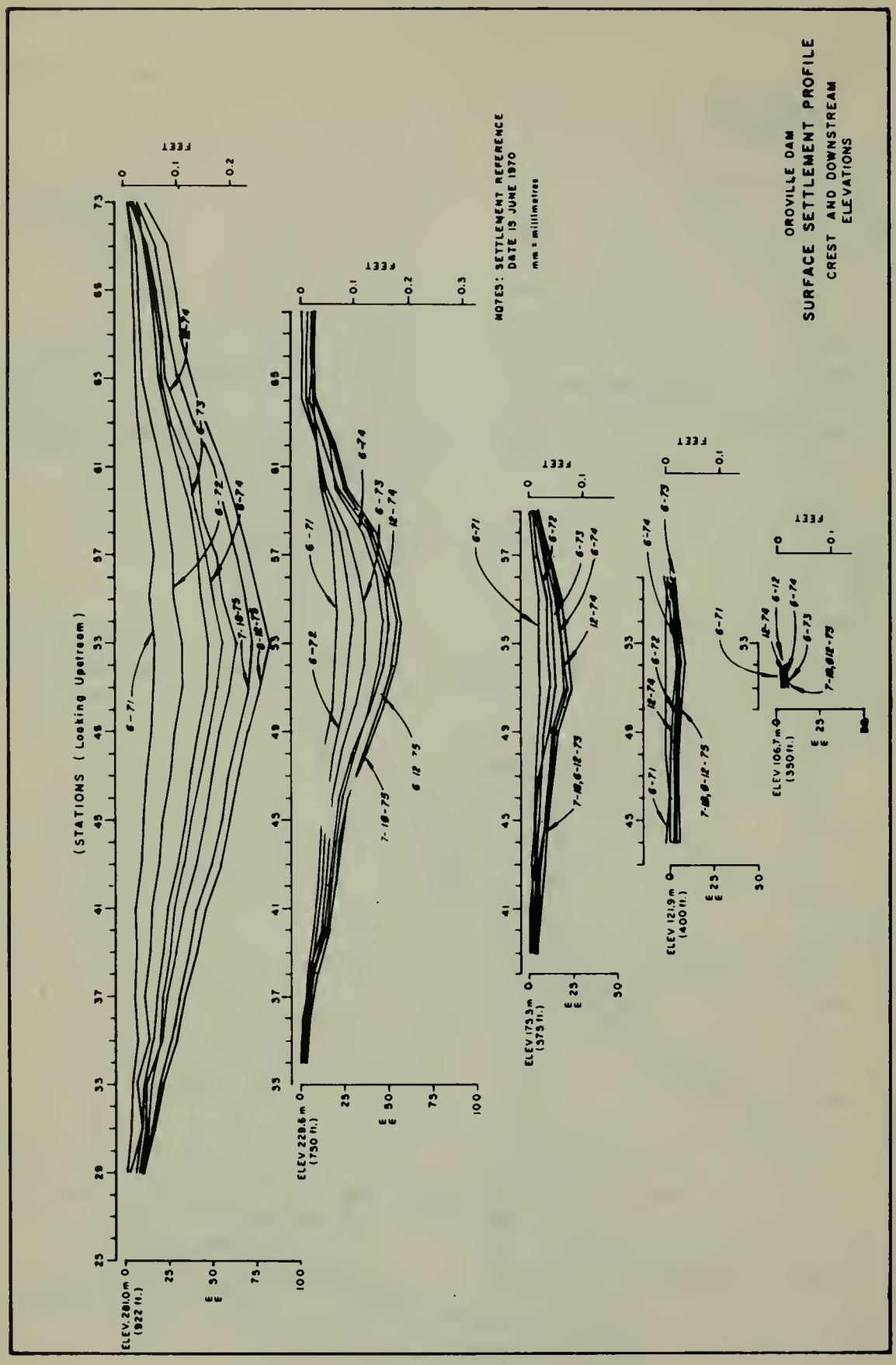


Figure 12. Surface Settlement Profile

movement with a maximum of 12 millimetres (0.04 foot) at Station 46.

Core Block

Static instrumentation in the concrete core block includes (1) stress meters to measure pressures imposed by the embankment soils on the concrete; (2) strain meters to measure deformation in the concrete surrounding the access gallery; (3) joint movement meters between monoliths; and (4) extensometers to measure movement across the crack beneath the parapet.

When the downstream fill above the core block was placed, pressures from that direction caused a rotation of the parapet and cracking occurred. The cracks and all the monolith joints in the core block were filled with grout.

A maximum stress increase of 405 kilopascals (59 psi) occurred near the heel of the core block between July 1, 1975 and August 2, 1975. The remaining meters generally showed small decreases in stress. Following the reading taken August 2, most meters showed that stresses tended to return to normal values.

Strains measured at the soffit and walkway of the core block access gallery were extremely small. The maximem change July 1, 1975, to August 18, 1975, was 27 millionths. The magnitude of these changes was within the range of those observed during three-month intervals before the seismic activity.

Extensometer readings taken after August showed that some small changes had occurred in the cracks and joints of the core block. The cracks opened a maximum of 0.1 millimetre (0.004 inch); the joints closed a maximum of 0.1 millimetre (0.004 inch). Most joint closures measure 0.025 millimetre (0.001 inch). By the end of August, these readings had returned to their normal val

Grout Gallery

Instruments in the grout gallery include (1) stress meters located at Station 8+24 and at Station 23+70 to measure stresses in the concrete lining of the gallery caused by loadings on the outside of the structure; (2) pore pressure cells at Station 23+70 to measure pressure at the rock-concrete interface; and (3) strain meters at variour stations to measure strain on the inside gallery surface.

Little change in stress occurred at the instrumented sections. The maximum change, 110 kilopascals (16 psi), is in line with changes which have previously occurred.

Pore pressure at the instrumented section increased 103 kilopascals (15 psi) upstream and 55 kilopascals (8 psi) at the downstream side.

One meter, located at the gallery soffit (Station 34+87), showed an increase in strain of 81 millionths after the first day of activity. All other changes were insignificant. Later readings generally indicated a return to original values.

Oroville Dam Spillway

Flood Control Outlet Pore Pressure

The pore pressure cells, located under the flood control outlet bays, show their normal pattern associated with the declining lake elevation.

Edward Hyatt Powerplant

Edward Hyatt Powerplant, whose position in relation to Oroville Dam is shown in Figure 13, consists of seven bays, one for each of the six generators and on one service bay. Instrumentation for each of the unit bays is shown in Figure 14.

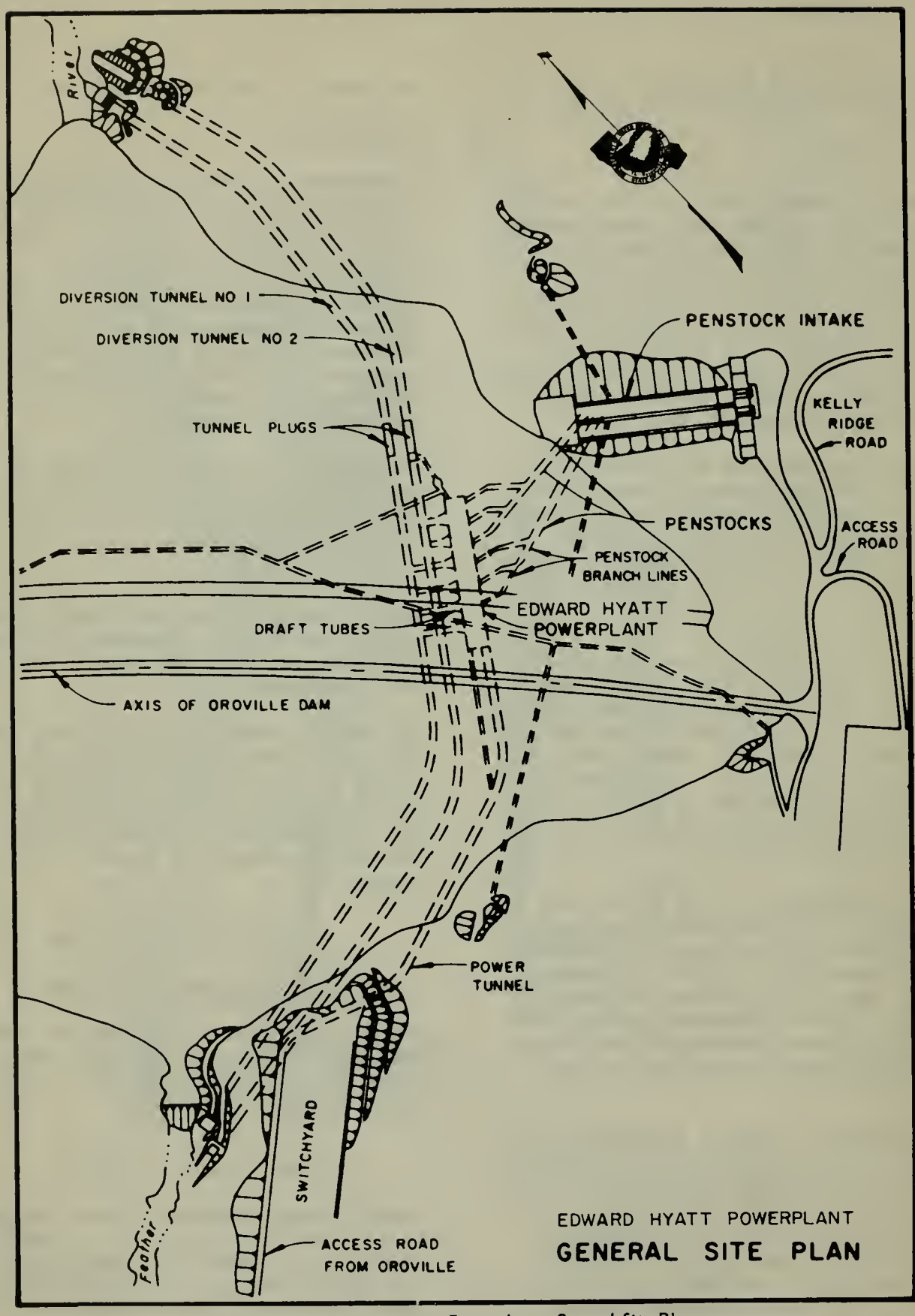


Figure 13. Edward Hyatt Powerplant - General Site Plan

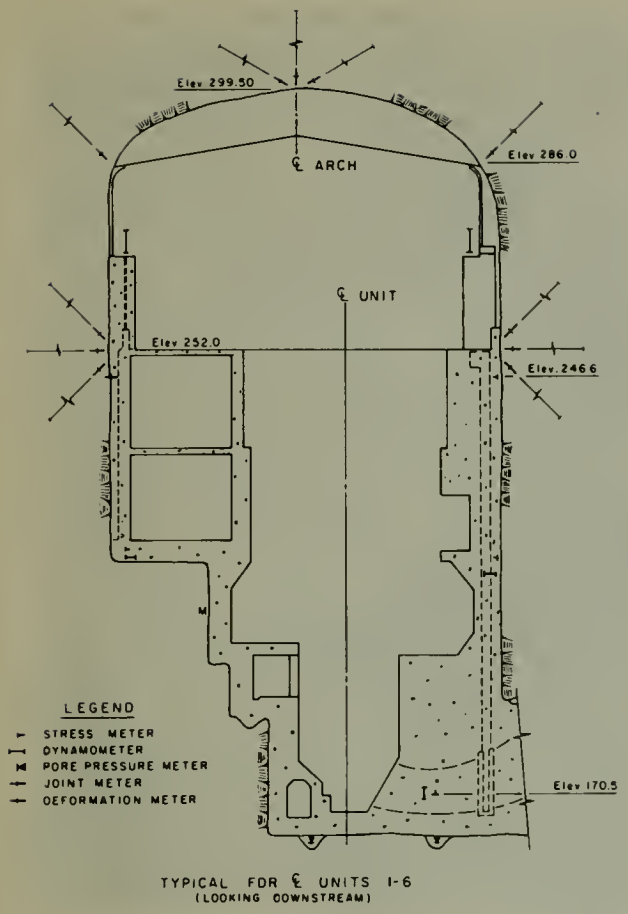


Figure 14. Edward Hyatt Powerplant - Location of Instruments

These instruments indicated that the earthquake and its foreshocks and aftershocks caused very little disturbance at the powerhouse. Seepage measurement at the power plant sump remained constant. Inspection of the underground power plant disclosed no damage or indication of distress. Small stalactites on the rock in the roof of the plant excavation, which can easily be loosened with only a slight touch, remained undisturbed.

Parish Camp and Bidwell Canyon Saddle Dams

These dams were inspected and found to be in good condition with no apparent damage.

Thermalito Diversion Dam

The monitoring of seepage, vertical and horizontal movements, and inspections verified that the Thermalito Diversion Dam came through the seismic activity in excellent condition. Monuments on the dam crest settled about one millimetre (0.003 foot) between June 1974 and August 25, 1975. The maximum offset during this period was 6 millimetres (0.02 foot) upstream. These movements are consistent with trend of movements occurring over prior years.

Seepage measured at the gallery sump pump increased from 28.4 to 36.0 litres (7.5 to 9.5 gallons) per minute between July 1975 and mid-August. This increase is attributed to the earthquake. Subsequent to the earthquake, the rate has steadily declined (Figure 15).

Feather River Fish Barrier Dam

The Feather River Fish Barrier Dam was inspected numerous times and was found to be unaffected by the seismic activity.

Thermalito Power Canal

Inspections of the power canal revealed no damage to the canal or slopes from the seismic activity.

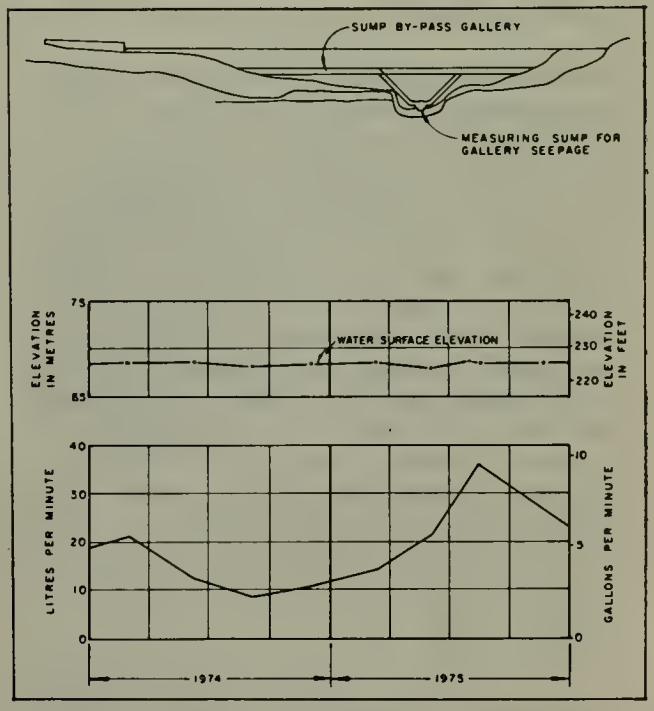


Figure 15. Thermalito Diversion Dam - Gallery Seepage

Thermalito Forebay Dam

Inspections of Thermalito Forebay Dam showed no damage, except for two minor cracks along top of slope at Station 123+00 and parallel to the riprap blanket. Piezometric levels downstream of the dam remained essentially unchanged during the period of activity. A few piezometers indicated a small drop, 0.3 to 0.6 metres (1 to 2 feet). This has been attributed to a lowering forebay level.

Drainage measurements remained constant at the two drains, seepage relief system, and the culverts into the tail channel.

Vertical movements of embankment monuments since May 1974 are small (a maximum of 3 millimetres /0.01 foot/) and follow similar trends of prior movements.

Thermalito Powerplant and Intake Structure

Inspection of the Thermalito Powerplant showed no damage or distress, except for minor spalling of concrete at wall panel joints.

Measurements taken immediately after the primary shock indicated no change in the well point water levels or total gallery drainage. Readings taken three weeks later, following a period of continued seismic activity, showed an increased average of 0.46 metre (1.5 feet) in nearly all well points and an increase of approximately 0.06 litre per second (1 gallon per minute) in total gallery drainage. The major increase is earthquake-related; however, an annual pattern has been established with higher rates (near 11 litres /3 gallons/ per minute) in winter and lower rates in summer. Readings taken after August 1975 appear to be typical of the annual pattern.

The stress meters, strain meters and uplift cells installed at the intake structure did not exceed any previous high values. Minor variations in the readings were measured due to the seismic activity.

The vertical control surveys on the intake structure from the initial survey in July 1971 to May 1974 (the last survey before the earthquake) have indicated uplift of about 3 millimetres (0.01 foot). Between the May 1974 survey and the survey made in August 1975, after the earthquake, increases to 3 to 6 millimetres (0.01 to 0.02 foot) were observed. The greatest increase was found at the right wingwall. The indicated uplift is probably due to minor settlement of the control bench mark.

Thermalito Afterbay Dam.

Inspections of the Thermalito Afterbay Dam showed a longitudinal crack on each side of the river outlet structure. These are believed to have resulted from the difference in rigidity between the embankment and the outlet structure. The cracks do not materially decrease the dam's integrity.

Several cracks found on the crest of the training levees downstream of the river outlet structure (Figure 16) were not entirely unexpected because the levees were not as highly compacted as the dam. The levees remained in a safe, operable condition.

The tail channel, which joins the Thermalito Powerplant with the afterbay, is lined with rock and an underlying layer of sandy bedding material. Numerous small slips noted in the rock lining do not constitute a major problem and do not hamper operations. The slopes and lining of the channel were under study before the earthquake occurred because stability problems had been previously encountered under extreme drawdown conditions.

The only instruments at Thermalito Afterbay Dam are open-tube piezometers downstream of the embankment and settlement monuments located on the outlet

Figure 16. River Outlet and Fish Barrier Weir

structures and on the adjacent embankment. The monuments were surveyed in December 1973 and on August 6, 1975. The maximum settlement for this period was less than 6 millimetres (0.02 foot). The settlement that occurred during the earthquake is unknown but obviously minor.

Open-tube piezometers located in areas adjacent to this reservoir are provided for monitoring ground water conditions. Observation intervals were not increased during this period.

Ongoing Studies

Analysis of Oroville Dam Dynamic Instrumentation Data

Acceleration records obtained at the base and at the crest of the dam have enabled determination of dynamic material parameters for Oroville Dam.

The shear modulus parameters are necessary input for dynamic finite element stability analyses and would be of great value for further analyses of both Oroville Dam and any other dams constructed of similar material. Using "Finite Element" techniques, the recorded rock motion measured was input to the dam foundation, and material parameters were varied, until agreement between calculated and recorded crest motion was attained.

Static stress analyses of the embankment were made and the calculated stress compared to those indicated by the instrumentation.

Reanalysis of Project Structures for Earthquake Safety

The performance of State Water Project

facilities during the August 1975 earthquake series indicates their ability to withstand seismic loading.

One important question, however, must always be asked: What would happen if a stronger earthquake occurred? To answer this question, a comprehensive investigation was undertaken to determine the maximum earthquake motion that could be expected to occur in the Oroville area and to analyze all critical structures for this section.

The Special Consulting Board review the seismic environment of the Oroville facilities and concluded that the following hypothetical seismic events could be used for safety review and are considered to be very unlikely events:

Richter Magnitude	Distance of Fault from Oroville Dam	Estimated Peak Acceleration at Oroville Dam
8.4	100 miles	0.05 g
8.0	80	0.06
7.25	35	0.15
6.5	local	0.60

A program for dynamic structural analysis of critical structures was implemented in cooperation with the University of California, Berkeley. The structures to be analyzed include Oroville Dam, Oroville Dam Spillway, Thermalito Diversion Dam, Thermalito Powerplant Headworks, Thermalito Forebay Dan, and Thermalito Afterbay Dam. Dynamic strength of material in Oroville Dam was determined by large-scale laboratory testing conducted by the University of California. Additional exploration and soils testing for the Thermalito Forebay and Afterbay Dams were conducted by the Department of Water Resources.

No structural stability problems are anticipated; however, because of the complexity of the study and the thoroughness necessary, no final results are now available.

Seismic Risk Analyses for Oroville Facilities

Structures whose failure would not produce catastrophic results were included under seismic risk analyses conducted by Professor H. C. Shah of Stanford University. Under these analyses, the major factors forming the basis of seismic loading criteria will be:

- Value of structure.
- Exposure time of structure to earthquake.
- Peak ground acceleration during earthquake.
- Probability of exceeding peak ground acceleration during the economic life of the structure.
- Modifications that may be made to structures. (Minimal damage should occur due to future seismic events).
- Cost of making modifications. (Changes should not exceed the damage, replacement and, operational costs that could be expected to be incurred by a future event).

The facilities included in the seismic risk analysis will be:

- Edward Hyatt Intake Structure
- Edward Hyatt Powerplant

Edward Hyatt Switchyard

Oroville Operations and Maintenance Center

Thermalito Powerplant

Thermalito Switchyard

Summary of Studies and Investigation

The following is a listing of the studies and investigations recommended by the special Consulting Board. These are being implemented by the Department and the estimated completion date is July 1, 1978, at a total estimated cost of 1.7 million dollars.

Investigation	Estimated Cost ($1,000)	
Design		
Reevaluation of earth motion for Oroville-Thermalito facilities	102	
Determine properties of materials in Oroville Dam	58	
Dynamic reanalysis of structures	371	
Develop emergency plans (cost included in other programs)		
Keep informed of results of research (earthquake-reservoir) (cost included in other programs)		
Subtotal		531
Seismological		
Reappraisal of seismic activity in the Oroville area	102	
Calibration explosion (to determine accurate epicenter)	40	
Graphical presentation of seismic records	3	
Permanent seismograph station at epicentral area	8	
Portable sensitive seismograph network	3	
Permanent sensitive seismograph system at Oroville Dam	37	
State Water Project emergency sensitive seismograph equipment	12	
Modification of embedded seismic instrumentation (Oroville Dam)	25	
Subtotal		230
Geological		
Determine extent of fault		
Verify nature, age of last movement, and extent of faults west of dam		
Mapping and trenching		
Investigate surface cracking		
Study ground water conditions in epicentral area		
Subtotal		539
Geodetic Surveys		
Precise surveys of Oroville area	400	
Subtotal		400
TOTAL ESTIMATED COST		$1.7 million

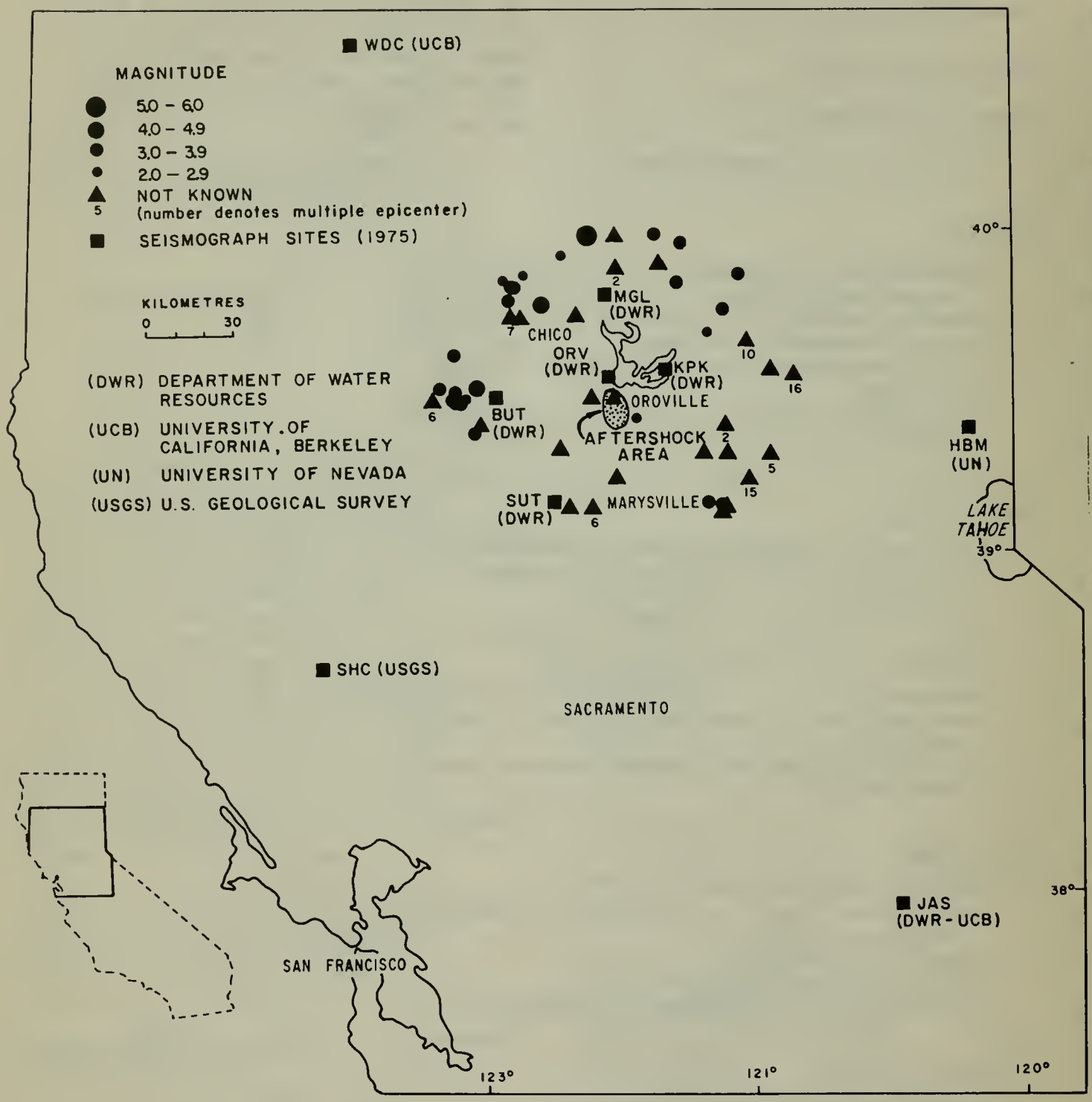


Figure 17. Historical Seismic Activity Near Oroville, 1851-1975, and Seismograph Network

Chapter III. SEISMOLOGY

The Oroville earthquake sequence began on June 28, 1975 with the occurrence of several foreshocks; the largest was magnitude 3.8 (Table I). The sequence appeared to die out (only five events took place between July 8 and August 1). Then on August 1, 29 foreshocks, the largest of which was magnitude 4.8, occurred within the five hours preceding the main shock. On August 1, 1975, at 2020 GMT (1320 PDT), the magnitude 5.7 main shock occurred about 12 kilometres (7.5 miles) southwest of Oroville Dam.

Historical Seismic Activity

Historical records indicate that the Oroville area is one of low seismicity. Figure 17 shows the incidence of seismic events occurring within 60 kilometres (38 miles) of the Oroville seismographic station (ORV) from 1851 to 1975. Seismicially, this area is about half as active as the State average for the same area. The plotted earthquakes are taken from the complete seismicity record (Appendix A) of the University of California, Berkeley, Seismographic Stations. The epicenters determined by instrument are shown as solid circles. Earthquakes known to have occurred on the basis of actual reports, e.g., newspaper stories, are indicated by triangles.

University of California at Berkeley seismographic stations were established in 1887 on Mt. Hamilton and at Berkeley. Additional California seismographic stations were established in the 1930s; however, not until the latter part of the 1940s did seismographic stations become sufficiently well distributed to make epicenter determinations routinely practical in the northern Sierra Nevada.

Apparently the largest Modified Mercalli (MM) Intensity value affecting the City of Oroville between 1851 and August 1, 1975, was V (Appendix B). The largest earthquakes in the Oroville vicinity occurred on January 24, 1875, and on February 8, 1940. The 1875 event was probably centered immediately southwest of Oroville and was reported to have been felt as far away as Carson City, Nevada. The 1940 event was a shock of 5.7 magnitude that occurred about 50 kilometres (31 miles) north of Oroville Dam.

Seismic Monitoring 1964-1976

The Oroville (ORV) seismographic station was established in 1963, about one kilometre (0.6 mile) north of the dam (Figures 17 and 18.) Instrumentation

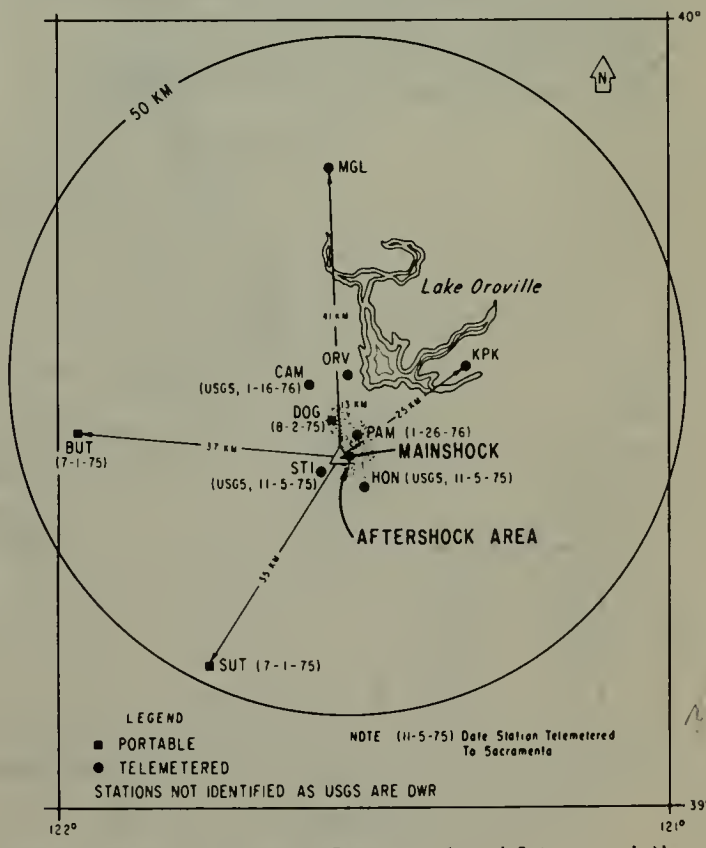


Figure 18. Department of Water Resources Local Seismograp' Network

similar to that used in World Wide Standard Seismographic Stations was installed by the U. S. Coast and Geodetic Survey at that time. Auxiliary stations Magalia (MGL) and Kanaka Peak (KPK) (Figure 18) were established in 1966 and telemetered by radio to the Oroville station. The portable stations Butte City (BUT) and Sutter (SUT) were established July 1, 1975, following the June 28 foreshocks. The station in South Oroville (DOG) was established August 2, 1975. Additional stations were subsequently telemetered to Sacramento, beginning with the USGS stations Stimson Road (STI) and Honcutt (HON) on November 5, 1975, Campbell Hill (CAM) on January 16, 1976, and another permanent Department of Water Resources seismographic station, Palermo (PAM), January 26, 1976, near the main shock epicenter.

Data recorded at ORV were analyzed at UC Berkeley Seismographic Stations from March 1964 through August 1968. With establishment of data recording and processing facilities, the Department of Water Resources began telemetering seismic signals from the dam network to Sacramento in July 1968. Subsequently, the seismographic records have been analyzed by Department personnel in Sacramento.

The results of seismic monitoring near Oroville are shown in Figure 19. The histogram shows numbers of earthquakes within 10-kilometre (6 mile) increments of radius out to 50 kilo metres (31 miles) and ORV (see also Figure 18). The general increase in seismicity after July 1, 1968, (evident in Figure 19) is in part real and in part attributable to increased recording system magnification that resulted when the Department of Water Resources began telemetering the Oroville station seismographic data to Sacramento in July 1968. The preponderance of this increase in seismicity is greater than 30 kilometres (19 miles) from the Oroville station and is well distributed azimuthally and in time. No

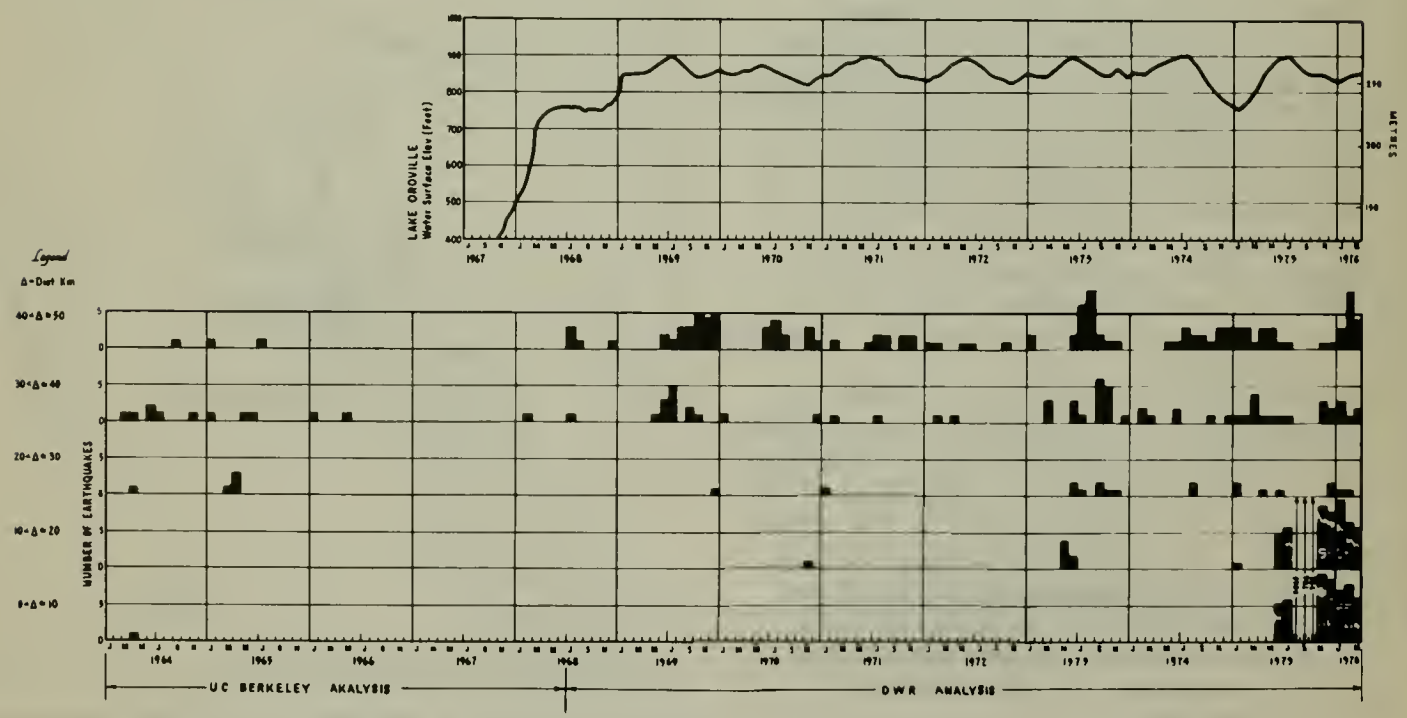


Figure 19. Analysis of Seismic Activity Near Oroville - Water Surface Elevation of Lake Oroville

increase in seismicity occurred in the 0-to-10-kilometre (6-mile) increment and only a slight increase is evident in the 10-to-20-kilometre (6-to-12-mile) increment.

The elevation of the water surface of Lake Oroville is also shown in Figure 19. From November 1967 until March 1968, the reservoir filled to about 229 metres (750 feet). The reservoir was first filled to capacity of 274 metres (900 feet) in July 1969. The largest fluctuation in level occurred in the winter of 1974-75, when the reservoir was lowered to 229 metres (750 feet) elevation. During the six-year period of near-maximum water storage, the histogram indicates no significant fluctuations in the local seismicity within a 30-kilometre (19-mile) radius of the dam. The very low level of local activity continued through the 1974-75 drawdown and refilling.

On June 28, the foreshocks of the Oroville sequence began. These events are shown in Figure 19 in the 0-to-10- and 10-to-20-kilometre (6-to-12-mile) ranges in June and July. For August, September, and October 1975, the number of aftershocks in 0-to-20-metre (12-mile) range (plus the 29 foreshocks) are represented numerically in Figure 19. During the first day or so following the main shock, the seismic traces of many quakes were obscured by previous events, so that epicentral distances were not determinable. Also, because of the large number of shocks, most of these events have not been analyzed. More than 4,000 aftershocks were recorded in the three months following the main shock. The great majority of these were below magnitude 2.0.

Earthquake Hypocenters and Magnitudes

Oroville earthquake hypocentral parameters and magnitudes from June 28, 1975, through March 31, 1976, are listed in Table I. [1/] The list includes all earthquakes of magnitude 2.5 or greater and a few smaller ones. A plot of epicenters of these earthquakes is shown in Figure 20. In the western part of the aftershock zone, the earthquakes are generally 8 to 9 kilometres (5 to 6 miles) deep. The depths become generally shallower toward the eastern side of the aftershock zone, indicating a fault plane dipping down toward the west.

The Richter 5.7 magnitude estimate of

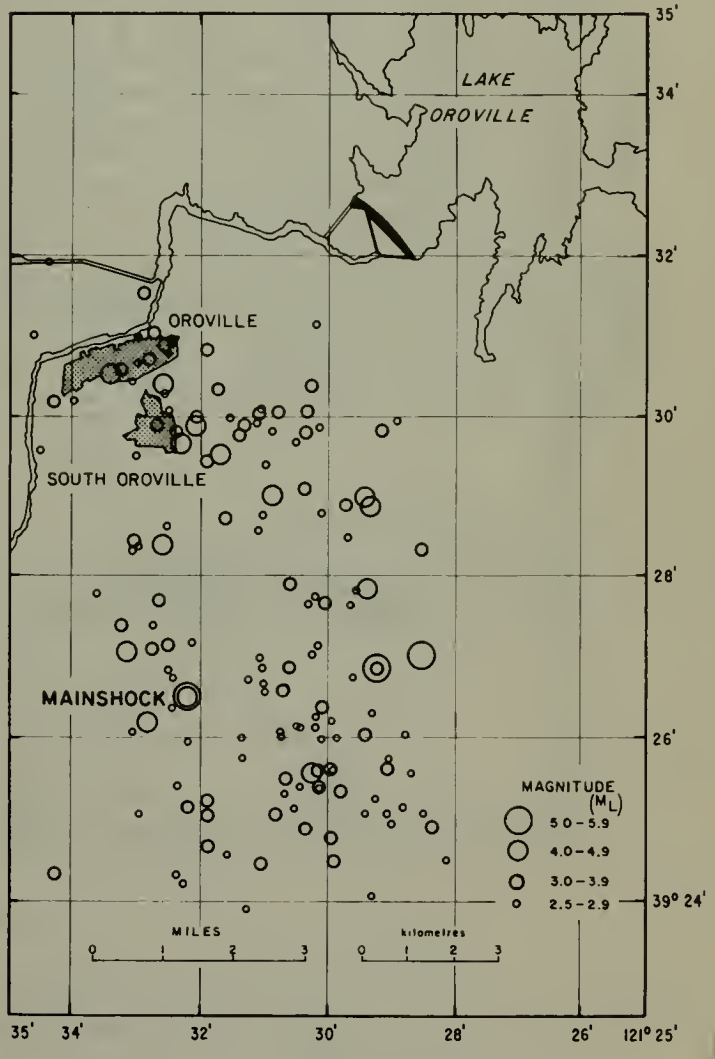


Figure 20. The Oroville Sequence of Epicenters - June 28, 1975 - March 31, 1976

1/ *Tables 1 and 2 follow Appendix B at the end of the bulletin.*

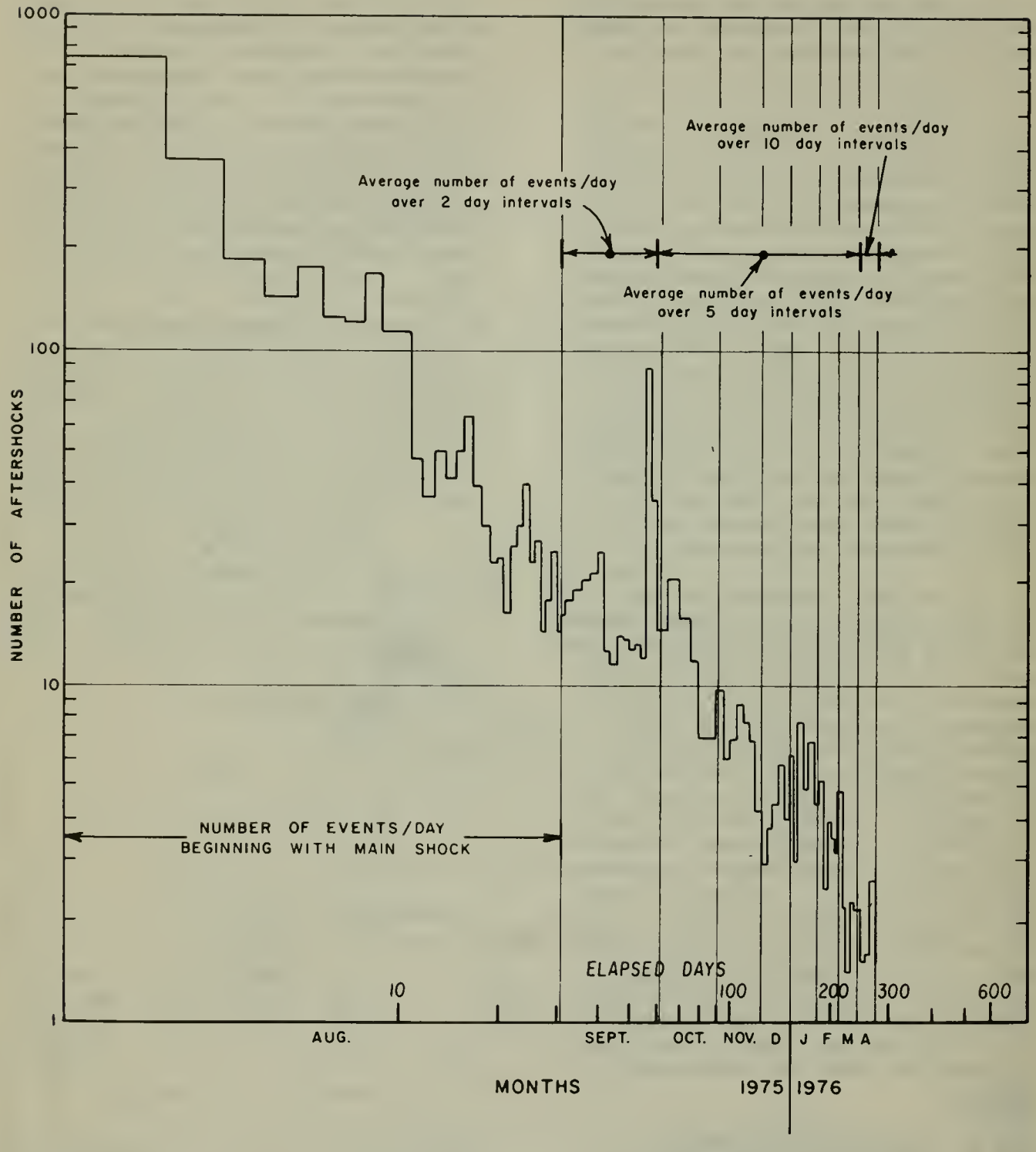


Figure 21. Oroville Sequence Time History

the main shock was determined at the UC Berkeley Seismographic Station by averaging the individual estimates from Wood-Anderson seismographs at Arcata, 5.7; Berkeley, 5.7; Mt. Hamilton, 5.6; and Stanford, 5.7.

The hypocenters listed in Table I were determined with the USGS HYPO 71 epicenter program, which evolved from the program in use at UC Berkeley. Station corrections were determined for the nine-station network shown in Figure 17 to improve the accuracy of hypocenter determinations. Using the station corrections in the epicenter determination of the magnitude 4.8 foreshock (8.1 seconds before the main event) moved the epicenter about 10 kilometres (6 miles) east of the uncorrected determination. Remaining systematic errors may be as much as 1 kilometre (0.6 mile) southwest from the actual epicenters. This possible error is indicated by (1) a calibration chemical explosion specially detonated within the aftershock zone, and (2) a comparison with USGS array locations, and assumes that the USGS network is sufficiently dense to result in more accurate determinations.

With the addition of HON, STI, CAM, and PAM to the network (Figure 18), the accuracy of the subsequent epicenter determinations is probably within 1 kilometre (0.6 mile). Also, the epicenters for more earthquakes below magnitude 2.5 were determined.

Earthquake Sequence Characteristics

Time History of the Sequence

The Oroville sequence included 21 foreshocks with magnitudes of 1.6 or greater, the main shock, and 158 aftershocks with magnitudes of 2.5 or greater through March 31, 1976. Seventeen aftershocks with magnitudes of 4.0 or greater were recorded during that time. The last aftershock with a magnitude of 4.0 or greater was recorded on November 15, 1975 (as of June 15, 1976).

Figure 21 shows the number of af
per day, recorded at the Oroville
beginning at the time of the magn
5.7 main shock. As the days becom
"compressed" by the logarithmic scale, the rate of occurrence per day is determined as an average over an increasingly larger number of days. A linear log-log relationship is indicated, with the projected rate of daily occurrence deminishing to one in about 500 to 600 days from the August 1, 1975, starting point. No lower magnitude limit is placed on the data. Most of the earthquake magnitudes are below 2.0.

Magnitude occurrence

Figures 22 and 23 show plots of the relation $\log N = a - bM_L$, where N is the cumulative number of earthquakes that are above and include some value of magnitude. The constants "a" and "b" are determined from data plotted in the figures. The value of "a" depends on the area in which the data were gathered, time duration, and the areal seismicity. The value of "b" is related to the proportion of large-to-small earthquakes in the data set. The value of "A" can vary considerably between regions,

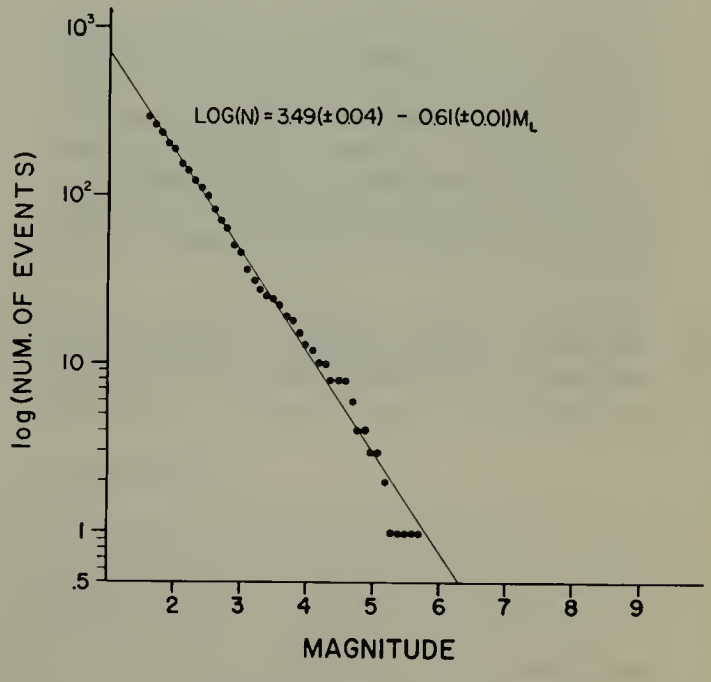


Figure 22. Oroville Aftershocks b Values

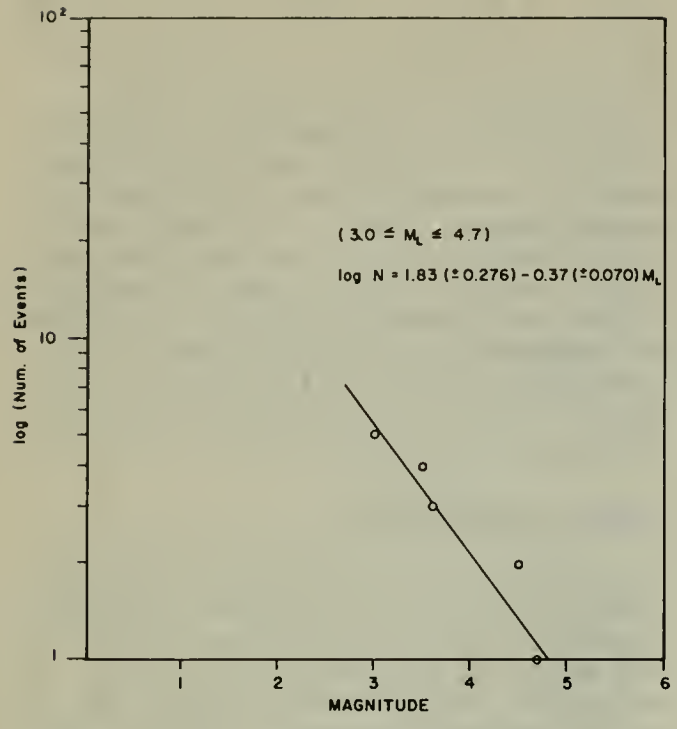


Figure 23. Oroville Foreshocks b Values

but "b" remains fairly constant, reportedly varying from 0.5 to 1.5, but chiefly between 0.7 and 1.0. The "b" values determined in Figures 22 and 23 appear in Table II.

In Figures 22 and 23, all magnitudes of 2.8 or greater values were computed from UC Berkeley Wood-Anderson seismographs. The smaller magnitudes were in all cases determined from the peak amplitudes recorded on short-period vertical instruments, using an empirical relation between magnitude and amplitude.

Because of the proximity of the Oroville earthquakes to Lake Oroville, the question of their possible relationship naturally arises. At this time, no satisfactory mechanism is available to explain the relationship between reservoirs and earthquakes that are apparently reservoir-induced. However, investigations into this relationship have shown what may prove to be significant differences between the b-factors of reservoir-induced earthquake sequences and "normally" occurring tectonic earthquake activity within the same region.

In Table II, b-values of three significant cases of reservoir-associated earthquake sequences (Gupta et al, 1976), and their respective regional values are compared with values for California sequences and regions. Note that the b-values of the Kariba (Africa), Kremasta (Greece), and Koyna (India) foreshocks are each greater than their respective aftershocks. Also, the b-values of these sequences are higher than their respective adjoining regional values. It may be significant then that the Oroville sequence foreshock and aftershock b-values are lower than the regional values for Northern California and that the Oroville foreshock b-value is less than the aftershock values.

Fault Plane Solutions

Preliminary results of fault plane solutions indicate that faulting involved in the Oroville sequence is predominantly normal, with a north-northwest strike and a dip of about 60 degrees to the west. The area west of the fault moved down in relation to the east.

Chapter IV. GEOLOGIC INVESTIGATIONS

Geologic Setting

Geologic History

The epicentral area of the August 1, 1975, earthquake lies along the western edge of the low foothills of the Sierra Nevada. The foothills become more rugged toward the east and finally grade into the main Sierra Nevada. To the west lies the broad Sacramento Valley.

Because much of the western foothill belt is underlain by Paleozoic and Mesozoic metamorphic rocks, it is frequently referred to as the western metamorphic belt of the Sierra Nevada. The older metamorphic rocks had their beginnings during Paleozoic time, when the Sierra Nevada region lay beneath a prehistoric sea and received sediments from both east and west. As the sediments accumulated, a north-trending synclinal trough began to subside and to fill with sedimentary and volcanic materials during the late Triassic and Jurassic periods.

During the Mesozoic era, granitic magma was generated in the synclinorium and emplaced in the Sierra Nevada plutons by a series of three intrusions, the last of which probably occurred about 85 million years ago. After the granitic rocks were emplaced, the ancestral Sierra Nevada was uplifted during the Nevadan orogeny. Erosion accompanying the uplift stripped away miles of material, exposing the granitic rocks seen today in the Sierra Nevada. A period of volcanic activity began in the northern and central Sierra Nevada about middle Oligocene time (about 30 million years ago) and continued into the Miocene. During late Pliocene, the northern Sierra Nevada was tilted strongly to the west. Erosion during the Quaternary period since this last stage of tilting formed the landscape seen today.

Other Interpretations of Geologic History

The scenario of geologic history described above has been the traditional one. During recent years, however, the concept of plate tectonics has gathered momentum and there is a growing trend to reexamine various geologic features, including the western foothill belt of the Sierra Nevada, in the light of plate-tectonic theories.

Some geologists suggest that the western foothill belt represents an old boundary, or subduction zone, between the Northern American and Pacific crustal plates, and that some Mesozoic oceanic crust crops out in what is interpreted to be an ophiolite sequence in the "Smartville Block". Others put forth the theory that the foothill metamorphic belt was a late Jurassic oceanic ridge which was telescoped by folding and faulting during the Nevadan orogeny. These various theories on the origin of the foothill metamorphic belt will be kept in mind as geologic investigations progress, because the differing concepts could influence subsequent analysis of tectonic style and seismicity.

Local Geology

The older metamorphic rocks in the western foothill belt are called the Bedrock Series. In the epicentral area, the Bedrock Series consist of an unnamed metavolcanic rock unit rich in amphibole minerals, and the Oregon City Formation, a series of metavolcanic and pyroclastic rocks. To the north, primarily around

the north borders of Lake Oroville, are outcrops of metasedimentary rocks of the Paleozoic Calaveras Formation. These three older rock units constitute most of the older rocks in the Oroville area. Typically, foliation in the metamorphic rocks has a northerly strike and steep dips.

Overlying the Bedrock Series are Cretaceous and younger sedimentary and volcanic rocks called the Superjacent Series. These rocks rest unconformably on the Bedrock Series and dip gently west beneath younger, flat-lying Pleistocene fluvial deposits of the Red Bluff Formation and Holocene alluvial deposits in the Sacramento Valley.

Geologic maps made prior to the Oroville earthquake show little faulting in the Oroville area. The more significant faults revealed by earlier geologic work, consist of three faults shown in Figure 25 in the Bedrock Series west of Oroville Dam. No faults were shown in the epicentral area.

Foothills Fault System

The major structural feature in the western metamorphic belt of rocks is the Foothills Fault System, which extends from the vicinity of Lake Almanor southward for approximately 320 kilometres (200 miles). The fault actually splits into two separate fault zones -- the Melones Fault zone to the east and the Bear Mountains Fault zone to the west (Figure 24). The Bear Mountains Fault zone ends at Folsom Lake. North of Folsom Lake, faulting, or a broad shear zone, is shown on various geologic maps as continuing northwest and ending southeast of the Oroville earthquake epicenter (Figure 24).

The northern part of the Bear Mountains Fault zone is reportedly intruded and truncated by both the Rocklin pluton of granodiorite and the Horseshoe Bar quartz diorite in the vicinity of Folsom Lake. Radiometric dates of rocks from these plutons have potassium argon dates of 131 and 142.9 million years, respectively, indicating that the northern part of the Bear Mountains Fault zone has not moved significantly for over 100 million years. In the Melones Fault zone to the east, most of the gold-bearing quartz veins that formed California's famed Mother Lode were emplaced in fissures related to the Melones Fault zone, and it has long been believed that no significant movement occurred along the fault system since the gold-bearing quartz veins were emplaced, about 100 million years ago.

Although geologic evidence suggested no significant fault movements had occurred along the Foothills Fault System for a long time, it was recognized that earthquakes occur along the foothill belt. The historic pattern of earthquakes from 1850 to 1970 shown on Figure 24 depicts the pattern of seismicity for 120 years prior to the filling of Oroville Reservoir. During this period of record, seismic activity was noticeably greater north of about Camp Far West Reservoir.

The few earthquakes of magnitude 4.0 or greater occurred in the north, and the largest event recorded was a 1940 earthquake which equaled the 1975 Oroville earthquake in magnitude. The 1940 magnitude 5.7 earthquake was 29 kilometres (18 miles) north of Lake Oroville. The greater seismic activity to the north may be due, at least in part, to volcanic influences, for it is near the Mt. Lassen area, the scene of surface eruptions in 1915.

Program of Investigation

Field Reconnaissance Immediately After Earthquake

Immediately after the Oroville earthquake, a team of DWR geologists went into the

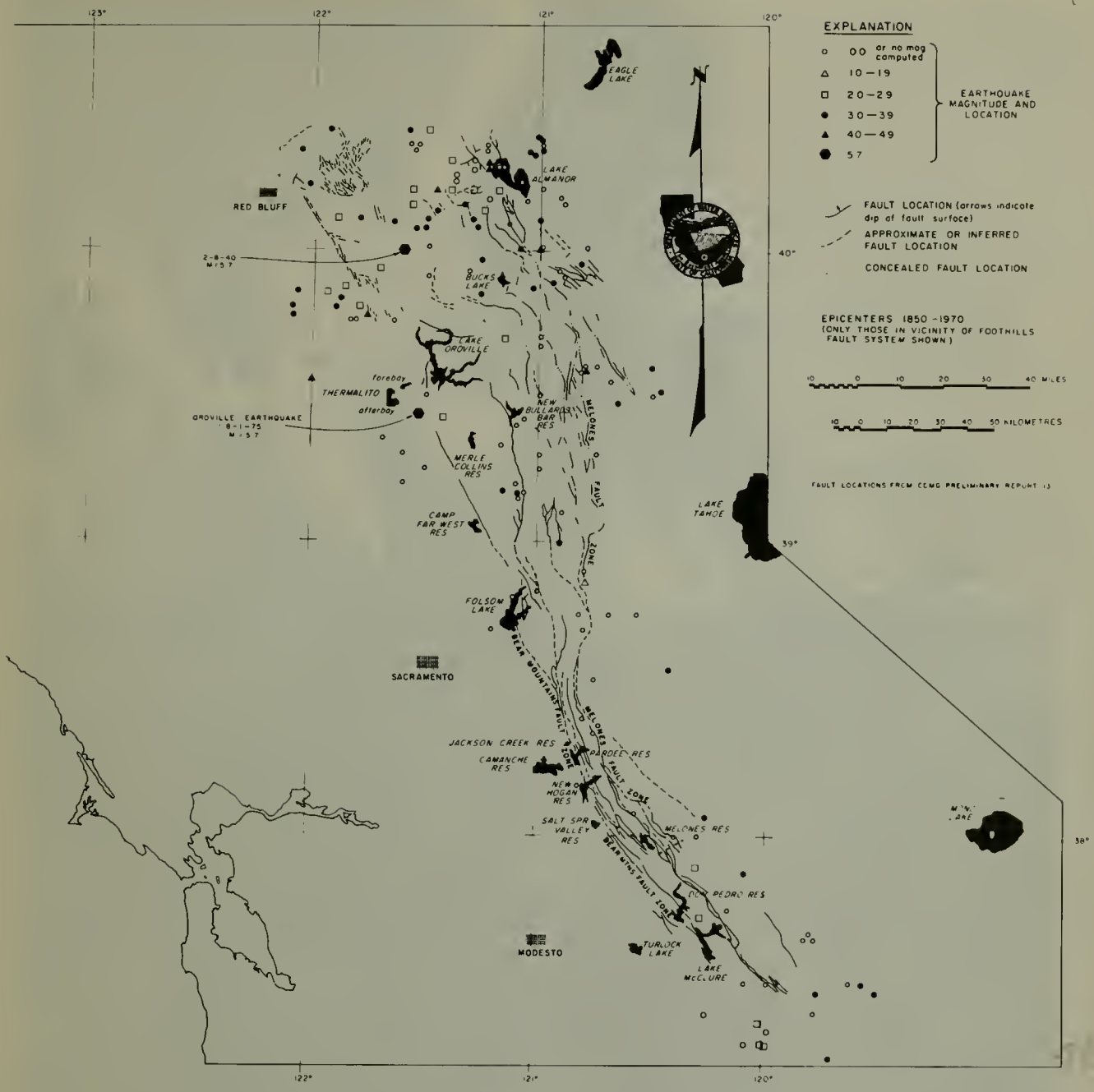


Figure 24. Foothills Fault System Showing Seismic Pattern and Locations of Reservoirs

field to look for evidence of surface fault movement and other fugitive geologic evidence that would be visible only briefly. A number of lurch cracks, fill settlements, and other types of cracking were investigated, but were not considered indicative of fault movement. On August 6, 1975, while following up a report from Butte County officials, Department geologists found cracks near Cleveland Hill south of Wyandotte. This crack system, which was apparently related to surface fault movement, was about 1.6 kilometres (1 mile) long and trended north toward Lake Oroville. An immediate check was made to see if the cracking extended farther north and was endangering

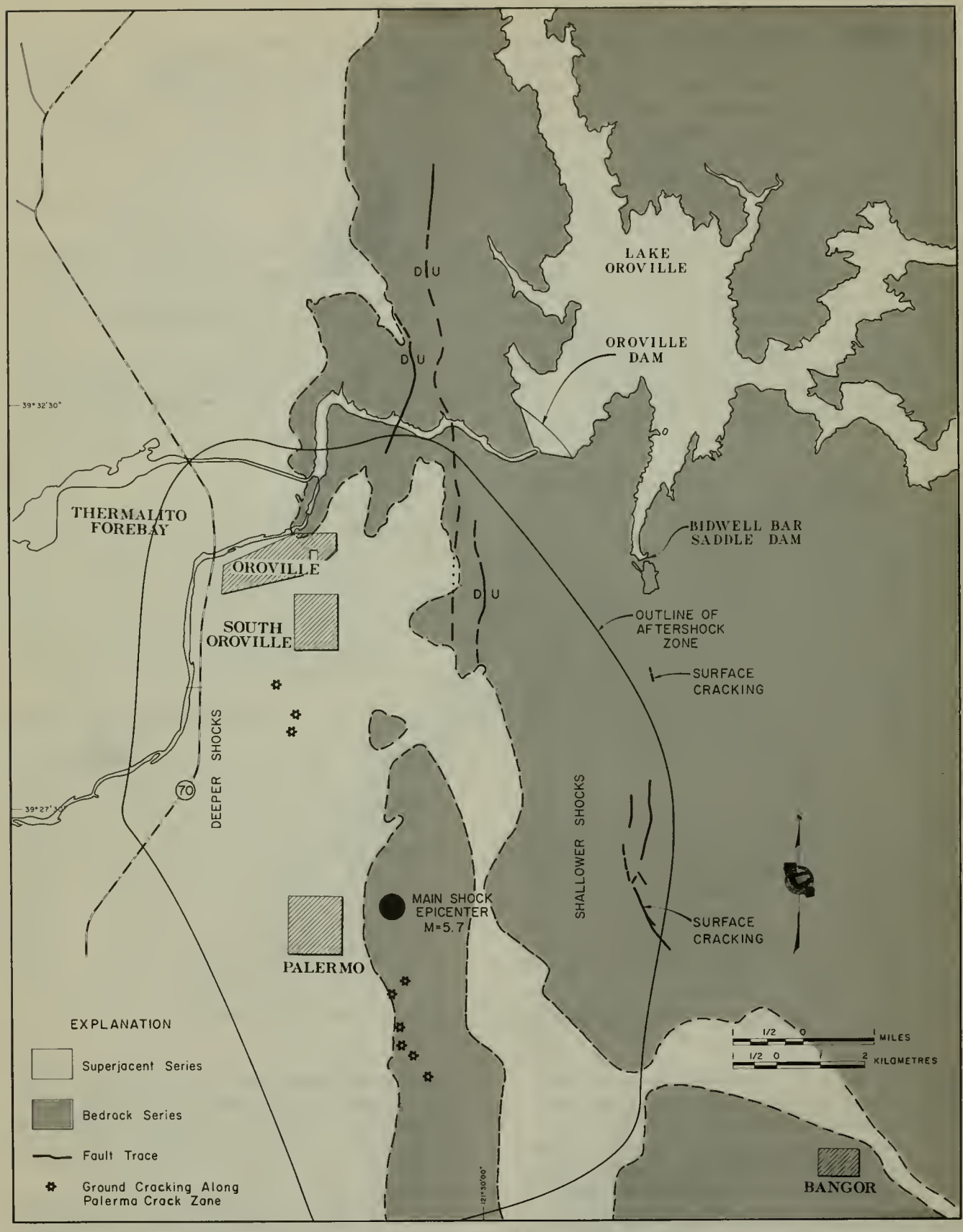


Figure 25. Generalized Geology Epicentrol Area, with Location of Mainshock, Aftershock Zone, and Ground Cracking

project facilities, but no cracking was found to the north. Three known faults west of Oroville Dam (Figure 25) were also checked for signs of surface movement, but no evidence of movement was found.

Several seeps started to flow just east of the larger fault on Oro Dam Boule ard, about 2.4 kilometres (1.5 miles) west of Oroville Dam (Figure 26). The Palermo Canal is upslope nearby, and water from the canal is believed to have leaked to the seeps from cracks newly opened by ground shaking or by strain along the fault immediately to the west.

Imagery and Photography

During the week after the Oroville earthquake, the Department obtained new black and white aerial photographs of the foothill area around Lake Oroville. Both vertical and low sun-angle photographs were taken with sufficient overlap to provide sterographic pairs. In addition, DWR obtained prints of aerial infrared (IR) color photographs taken previously in the Oroville area from U-2 planes. ERTS/LANDSAT remote sensing imagery of the area was obtained, first in band 5 and later in false color composites using bands 4, 5, and 7. Side-looking airborne radar (SLAR) imagery of the Oroville area was obtained from Woodward-Clyde Consultants in Oakland, California.

The photography and imagery were examined for lineaments,which were plotted on topographic maps. Field inspections were then started to see if the lineaments appeared to be faults. Exploratory

Figure 26. New Seep That Started in Metavolcanic Rock Along Oroville Dam Boulevard, 2.44 kilometres (1.5 miles) West of Oroville Dam Crest

trenches then were planned along suspected lineaments to confirm faulting. For the Oroville investigation, lineaments were laid out on topographic maps for some distance south of the reservoir. The follow-up, with field investigations and trenching, has been done only between the Cleveland Hill cracking and Oroville Dam and Lake, because the most essential task was tracing the active fault toward these facilities.

From all the lineaments plotted during early geologic investigations, there were three strong northerly trending lineaments that caught the attention of all investigators and received most of the subsequent geologic investigations. Portions of these three lineaments were named the Swain Ravine, Paynes Peak, and Prairie Creek lineaments by Woodward-Clyde Consultants, for geographic features in their study locale. The same nomenclature is used in this report, but is applied to apparent northerly extensions of Department of Water Resources interpretations of the same features (see Figure 58 on page

Coordination With Other Agencies

To avoid duplication of work, and to help implement a large, difficult investigation, certain aspects of the work were coordinated with other state and federal agencies.

California Division of Mines and Geology

Because good detailed geologic maps of the epicentral area were lacking, the California Division of Mines and Geology was asked to perform geologic mapping in the vicinity of the epicenter, mainly in the foothill parts of the Bangor and Palermo quadrangles. This work is still in progress.

U. S. Geological Survey

For several weeks after the earthquake, a team of U. S. Geological Survey geologists and seismologists worked in the field gathering data. The U. S. Geological Survey investigations centered primarily on seismological consideration. As a consequence, the two agencies are coordinating chiefly seismological endeavors which are discussed in Chapter III, Seismology, of this bulletin.

U. S. Army Corps of Engineers and U. S. Bureau of Reclamation

Auburn Dam is now under construction on the American River by the Bureau of Reclamation. The U. S. Army Corps of Engineers is investigating the possibility of a dam at the Parks Bar site on the Yuba River, and has New Melones Dam under construction farther south. All three projects are influenced by the Foothills Fault System. Because of this, the Bureau, the Corps, and the Department of Water Resources have a mutual interest in evaluating seismicity of the Foothills Fault System. Consequently, the three agencies confer every month or two and exchange information from their studies of the Foothills Fault System.

Woodward-Clyde Consultants

Woodward-Clyde Consultants had previously made a preliminary investigation of the seismicity of the Foothills Fault System for the Pacific Gas and Electric Company. After the Oroville earthquake, they studied the U. S. Corps of Engineers' Parks Bar damsite and then launched into larger, more comprehensive studies for PG&E, the U. S. Bureau of Reclamation, and the U. S. Army Corps of Engineers. Both Woodward-Clyde and their clients have been most cooperative in exchanging information of interest to the Department of Water Resources.

Cleveland Hill Crack Zone

The ground cracking found along the fault at Cleveland Hill on August 6 occurred either during or shortly after the Oroville earthquake. Ground cracking

Figure 27. Closeup of Clevelond Hill Crock. Moximum Opening 24 millimetres (0.95 inch)

Figure 28. Clevelond Hill Crack Zone Showing Downdrop on West (Left) Side of Crack

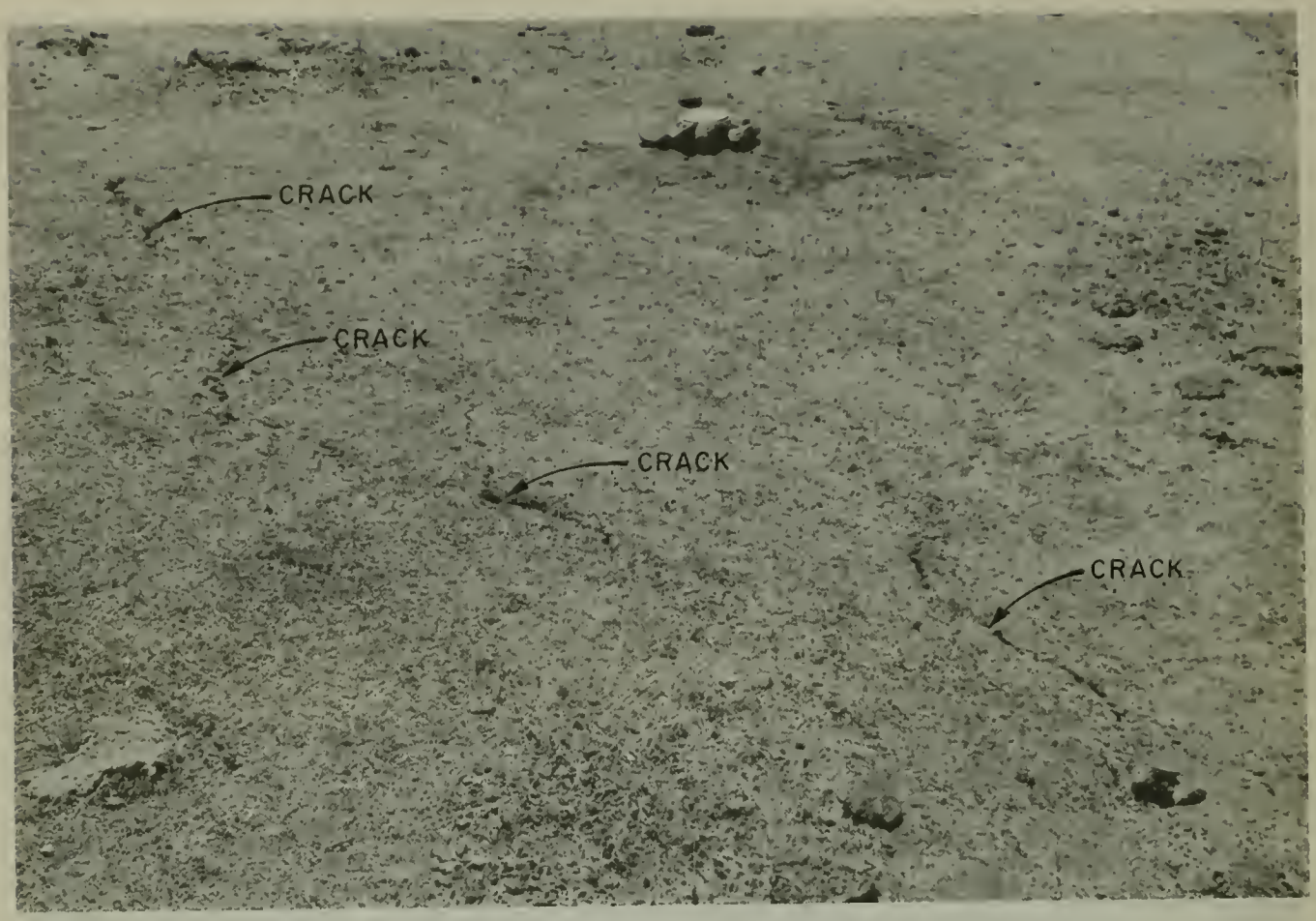


Figure 29. Cleveland Hill Crack Zone Showing en Echelon Crack Pattern with Right Lateral Sense of Movement USGS Bench Mark in Background

near Cleveland Hill consisted of en echelon cracks in a zone varying from about 1.0 metre (3.0 feet) to 7 metres (22.5 feet) wide and 1.6 kilometres (1.0 mile) long. A southeast-trending branch near the midpoint extended for 200 metres (610 feet). After about 6 weeks, the cracks widened to about 40 millimetres (1.6 inches), and in several places, the west side had dropped as much as 30 millimetres (1.2 inches). By the middle of October nearly all the crack system was displaced visibly downward on the west side. The general lift-stepping en echelon crack pattern suggests a right-lateral strike slip movement (Figures 27, 28, and 29).

Four trenches were dug at locations along the Cleveland Hill crack zone (shown on Figure 30) to confirm that the surface cracking was related to a fault (Figures 31 through 37). Three of the trenches (Trenches A, B, and D; Figure 31) were excavated through shallow colluvium and into weathered bedrock. The fourth trench (Trench C) was dug in deep, loose colluvium with high ground water and was not logged.

The three trenches in bedrock encountered a steep, west-dipping fault zone about 2 metres (6.5 feet) wide in metavolcanic rock. The surface cracking was either over or near the gouge zone in the fault exposed by the trenching. No cracking or displacement could be seen in the gouge zone. The lack of visible cracking in the gouge could have been caused by the obliteration of hairline cracks by the cutting action of the backhoe.

Because of the irregular contact between the overlying soil and the metavolcanic rock, past movements, particularly small

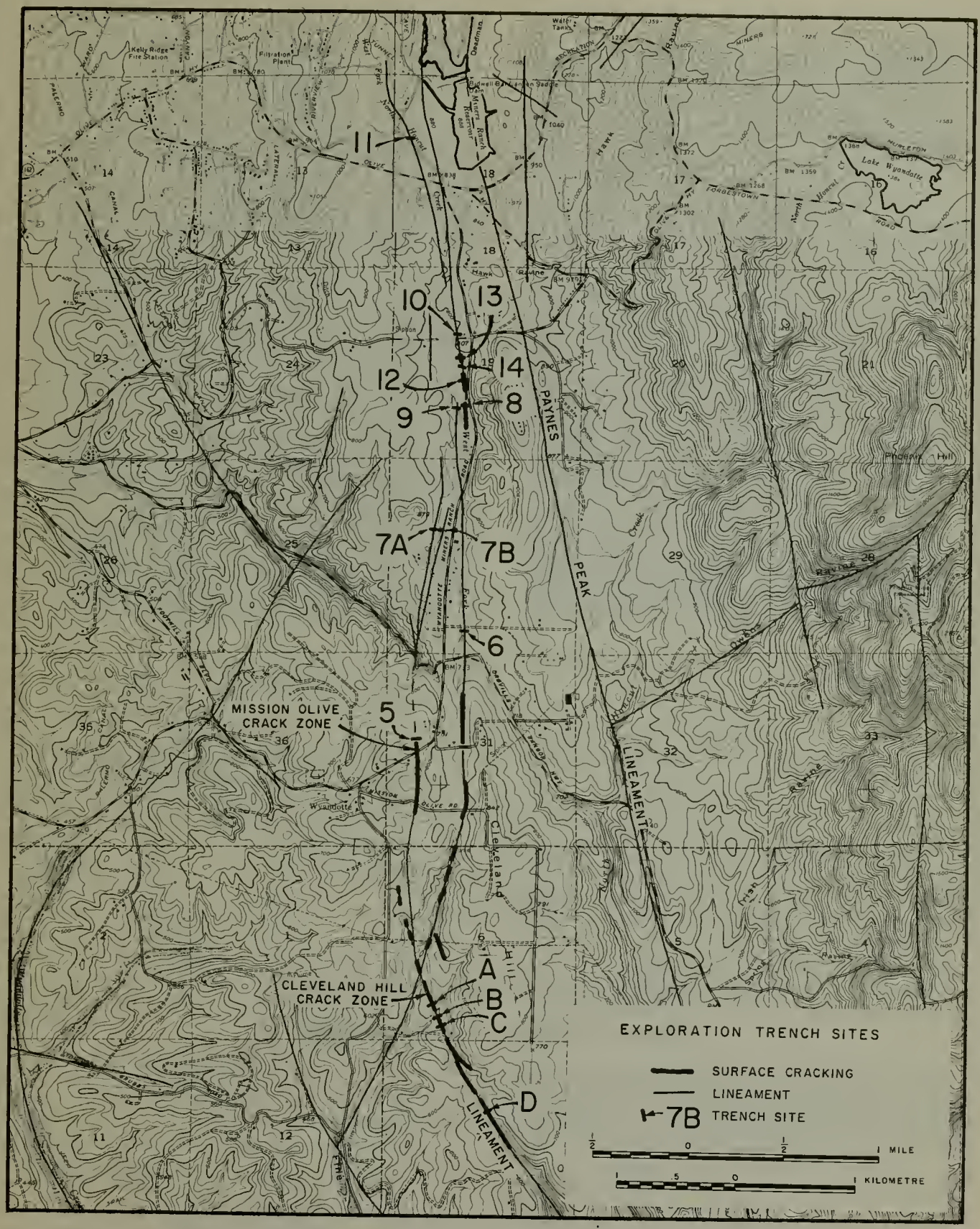
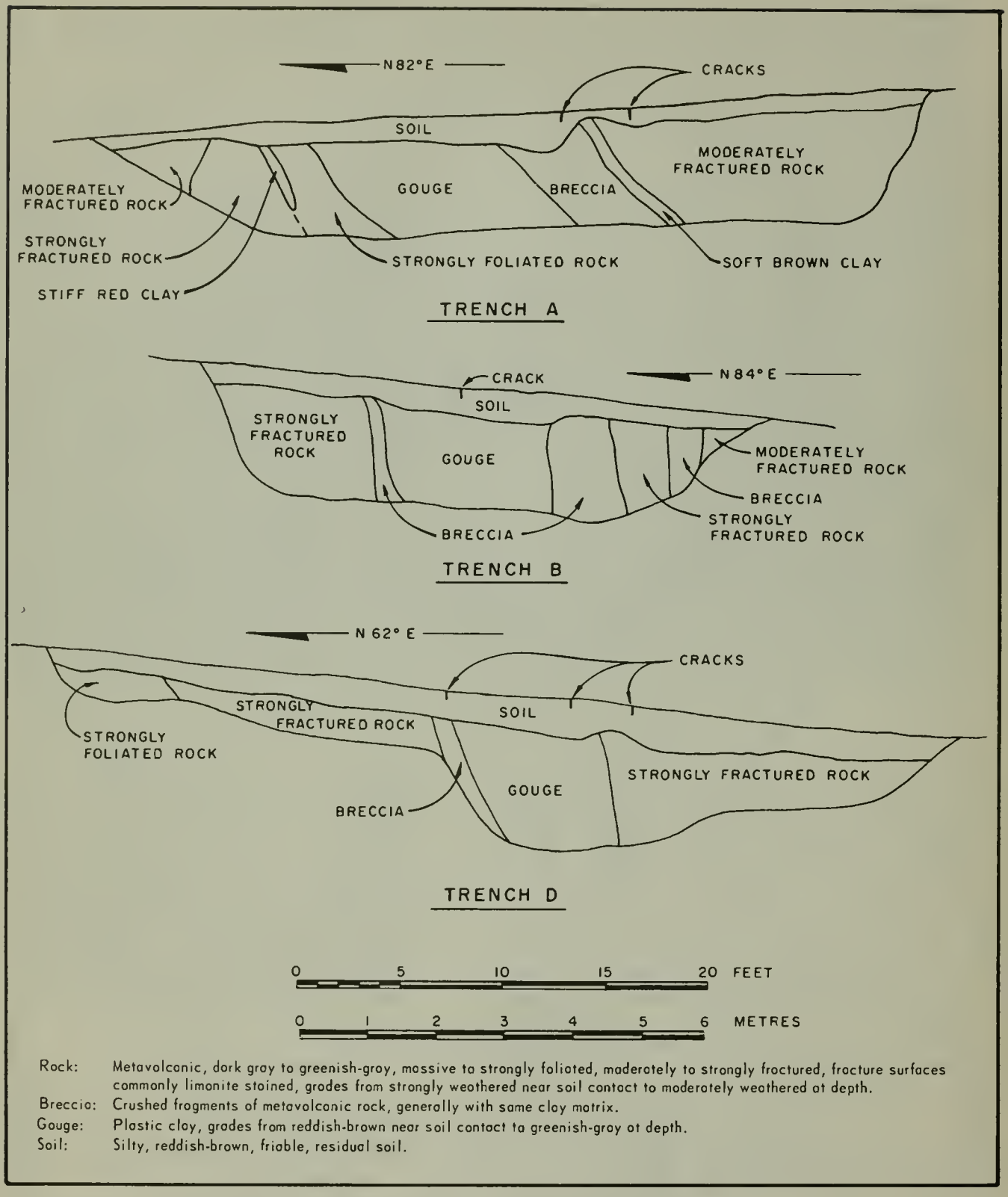


Figure 30. Location of Cleveland Hill and Mission Olive Crack Zones and Sites of Exploration Trenches



Rock: Metavolcanic, dark gray to greenish-gray, massive to strongly foliated, moderately to strongly fractured, fracture surfaces commonly limonite stained, grades from strongly weathered near soil contact to moderately weathered at depth.

Breccia: Crushed fragments of metavolcanic rock, generally with same clay matrix.

Gouge: Plastic clay, grades from reddish-brown near soil contact to greenish-gray at depth.

Soil: Silty, reddish-brown, friable, residual soil.

Figure 31. Logs of Exploration Trenches Along Cleveland Hill Crack Zone

Figure 32. Trench B, Showing North Wall. Smooth Surface of Trench Wall in Bottom Half of Picture is Gouge Zone, Lath of Right Side Marks Location of Surface Crack

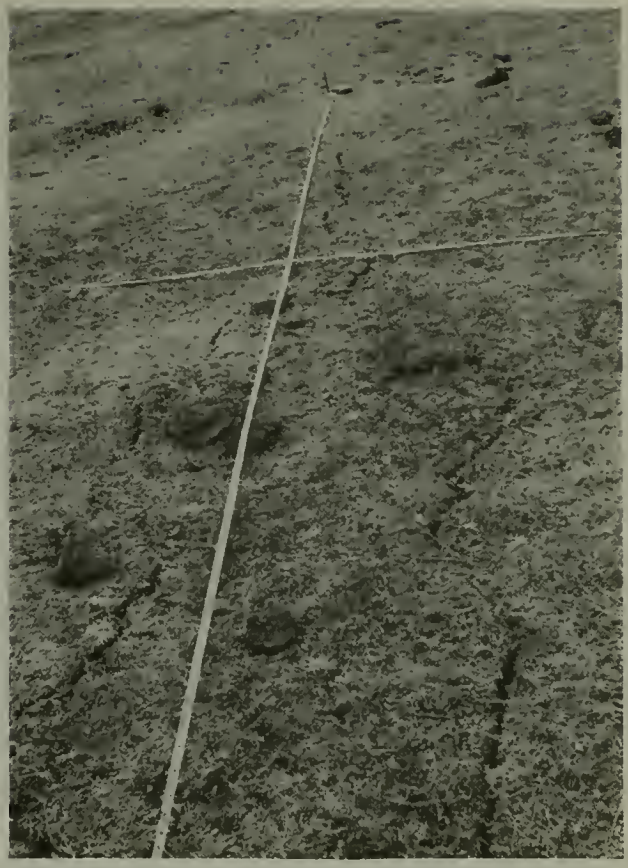


Figure 33. Trench Site D, Cloth Tape Along Trend of Crack Zone, Trench Location Marked by Folding Rule

movements, are difficult to detect by displacement of the soil-bedrock contact. Moreover, the thin soil cover did not contain distinctive marker horizons that could be correlated with certainty. The three Cleveland Hill trenches indicate that no obvious movement occurred since the soil formed on the metavolcanic rocks. However, small displacements such as those developed by the August 1, 1975 earthquake, could have occurred numerous times during the past without leaving evidence in the geologic record.

The metavolcanic rocks broken by the Cleveland Hill Fault are presumed to be upper Paleozoic in age, although this presumption is based upon rather tenuous evidence -- primarily the degree of metamorphism and the relationship to other formations. This would make the metavolcanic rocks around 300 million years old, and few would deny that the rocks are old, even though an upper Paleozoic age might be debatable. This means the Cleveland Hill Fault developed some time during the last 300 million years. If the northerly extension of the Bear Mountain Fault is intruded by the 131-million-year-old Rocklin pluton, then the Bear Mountains Fault zone and other faults in the foothill belt, such as the Cleveland Hill Fault, may have formed some time between 300 and 131 million years ago.

The history of fault activity during more recent geologic times is difficult to determine. The fault at Cleveland Hill does not have the obvious earmarks of a recently active fault, such as sharp distinct scarps, displaced Holocene deposits, or disrupted stream gradients. Along much of the Cleveland Hill cracking, there is little visible evidence to suggest faulting, but a

Figure 34. Ground Cracks at Trench Site D Accentuated with Paint for Photograph

Figure 35. View along Cleveland Hill Fault Showing Trenches A, B, and C. Although slight break in slope in vicinity of Trench B is interpreted by some as possible old fault scarp, topographic evidence of past faulting is generally lacking in this area.

Figure 36. Cleveland Hill Crack Zone goes between two USGS bench marks near fence and to right of trailer in background. Note absence of features that would suggest recent movement in this area. View looking north from vicinity of Trench D).

Figure 37. Cleveland Hill Crack Zone in foreground goes beyond fence to dark spot (seep) in grass beyond fence. Seep and gully are features charocteristic of fault zone. Strong lineament extends south of gully. View looking south from vicinity of Trench D.

seep and linear topographic depression, or gully, at the south end, are typical geomorphic expressions of faulting.

Both the trenching and the topography indicate large displacements have not occurred along the fault zone since the present soil developed upon the bedrock surface. In other words, geomorphic processes proceeded at a faster rate than fault movement, suggesting that fault displacements were small and/or infrequent during the current erosional cycle.

Relationship of Cleveland Hill Cracking to Earthquake

As shown on Figure 25, the main epicenter of the earthquake occurred 7 kilometres (4.3 miles) west of the surface cracking seen near Cleveland Hill. Most of the aftershocks occurred in a zone starting at the zone of surface cracking and extending west as shown on Figure 25. The aftershocks occurred at a shallower depth in the eastern part of the zone and at greater depths in the western part of the zone.

The surface cracking, the main earthquake hypocenter, and general distribution of aftershocks at depth suggest a fault dipping about 60 degrees west and striking about 25 degrees west (Figure 38). This is compatible with first-motion analyses developed by

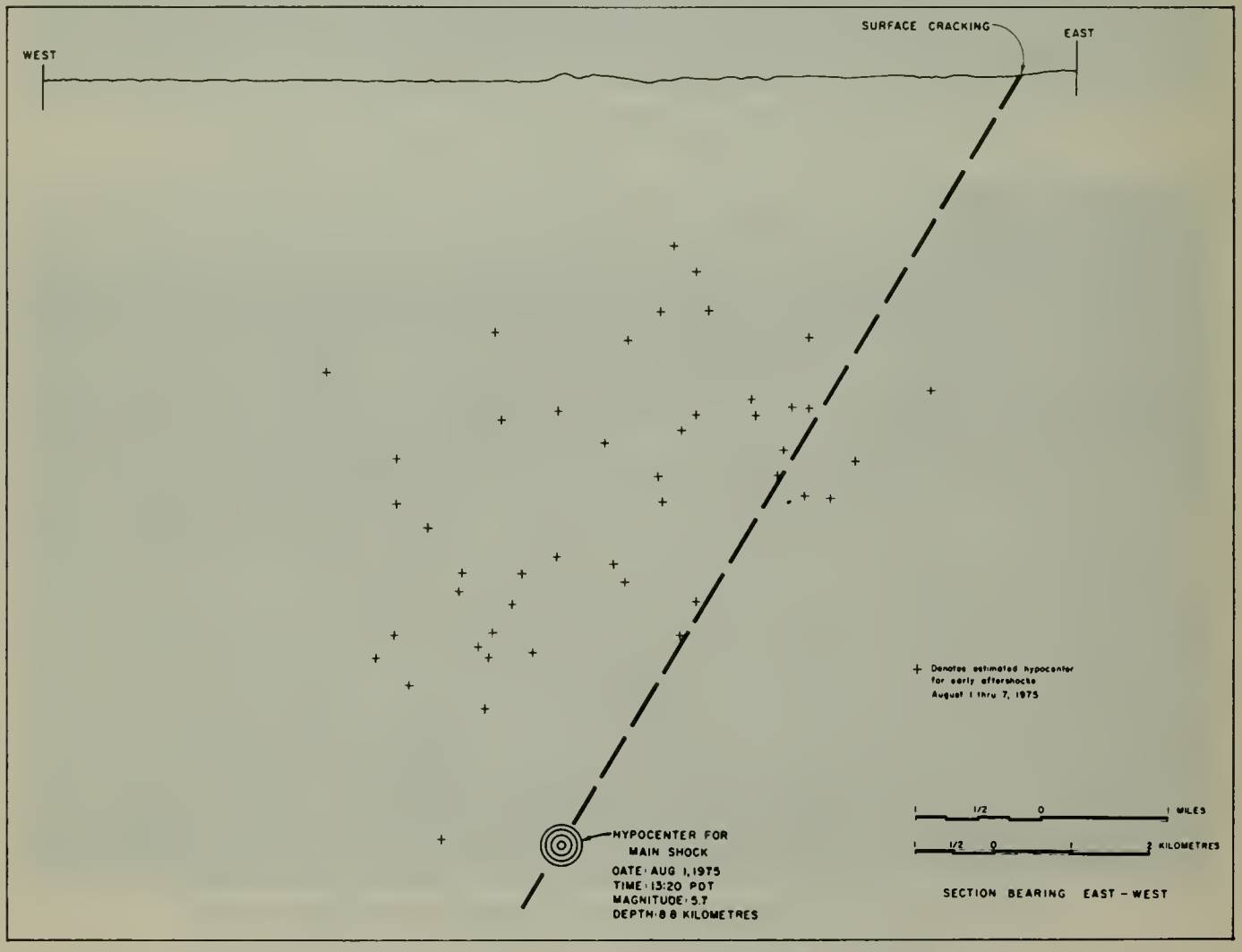


Figure 38. Relationship of Cleveland Hill Cracking to Mainshock Hypocenter

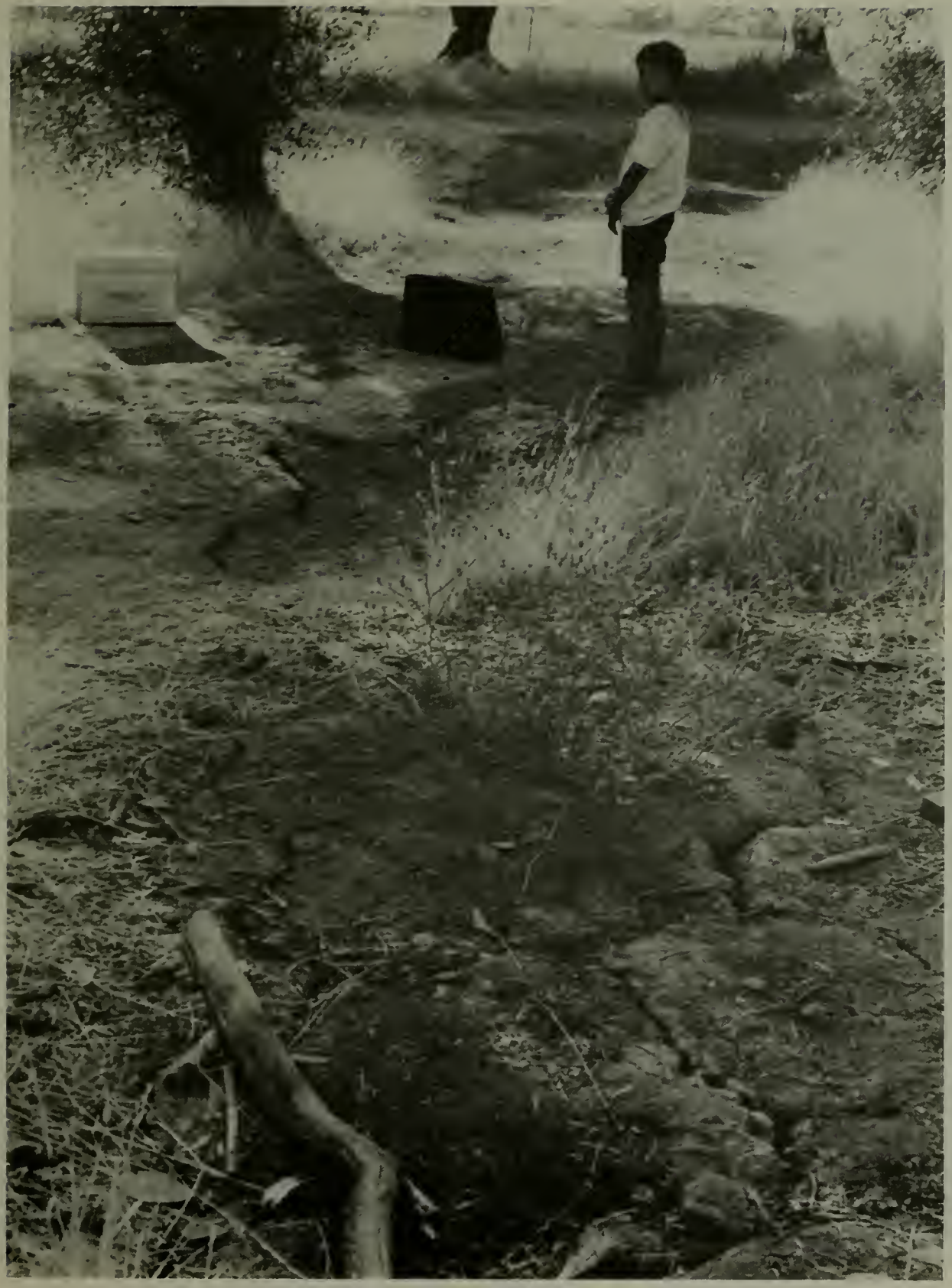


Figure 39. Local Ground Cracking on Zumwalt Property along "Palermo Cracking Zone"

Figure 40. East Crack Zone on Mission Olive Road

Figure 41. Mission Olive Crack Zone Across Paving on Foothill Boulevard

most seismologists. It is presumed that the Cleveland Hill cracking is along the fault, or one of the faults, related to the Oroville earthquake of August 1, 1975. Because of its importance, the entire Cleveland Hill crack zone was mapped at a scale of one inch to 10 feet during late August and early September.

Palermo Crack Zone

Field verification of reports of ground cracking after the earthquake failed to reveal any fault movements other than the Cleveland Hill cracking. When the various lurch and settlement cracks investigated were plotted on a map, one group of ground cracks formed a northwest-trending alignment from Palermo to South Oroville, roughly following the western toe of the foothill metamorphic belt. This alignment of cracks ranges from faint cracks diagonally crossing roadways to distinctive cracks extending tens of of metres. There were some areas of strongly shattered ground, with cracks open to 75 millimetres wide (3.0 inches).

This crack zone, the "Palermo Crack Zone" (Figures 25 and 39), is of particularly interest, because it falls along the northwest projection of the Prairie Creek lineament, a strong lineament that extends some distance southward and along the approximate west boundary of a large shear zone shown on the Chico sheet of the Geologic Map of California. The cracks also line up roughly with a northwest trending series of faults in the Pliocene Formation to the northwest.

The linear arrangement of ground cracking along a lineament and its relationship to mapped faults to the north and south give rise to the suspicion that a throughgoing northwest-trending fault system may lie underneath the "Palermo Crack Zone". Such a fault system could be hidden by younger, unbroken, Pleistocene Red Bluff Formation and Holocene alluvial deposits.

Continuation of Ground Cracking After Earthquake

Early in October 1975, two roughly parallel crack zones were found north of the Cleveland Hill cracking. The new cracks, called the Mission Olive crack zone, were about 400 metres (1,300 feet) apart and had a northerly strike (Figure 30). The cracks are similar to the original cracking near Cleveland Hill but are not as continuous. They extend intermittently about 2.0 kilometres (1.25 miles) north and break the asphalt pavement where they cross Mission Olive Road (Figure 40). The westerly crack zone also breaks the pavement on Foothill Boulevard farther to the north (Figure 41). Neither road was cracked in August when all paved roadways north of the Cleveland Hill crack zone were inspected for cracking toward the Oroville facilities.

In February 1976, another 182 metres (600 feet) of new cracking was found south of Mount Ida Road during inspection of a proposed trench site along the lineament extending north from the east branch of the Mission Olive crack zone (Figure 30). The short crack zone was 2.7 kilometres (1.7 miles) from Lake Oroville. This northern crack was not present in October 1975, when the area was visited by a Department of Water Resources geologist and a site selected for Trench No. 8.

When first found on February 9, 1976, the cracks appeared very fresh. When examined again on February 20, 1976, the cracks were much more difficult to follow, partially because of rain and the growth of new grass. It is estimated the new cracks probably occurred during the first week in February 1976. In August 1976, several hundred more feet of apparently fresh cracking was found to the north.

Known ground cracking now totals 6.6 kilometres (4.1 miles) and has progressed to within 2.3 kilometres (1.4 miles) of the Bidwell Canyon Saddle Dam at Lake Oroville.

Because the precise time of cracking is not known, the progressive northward cracking cannot be related to any particular aftershock or series of aftershocks. The progression may be caused by a lag in strain adjustments being propagated updip along the fault system from the main shock hypocentral area to the ground surface.

Geodetic Work

Immediately after the Oroville earthquake, survey crews from the Department of Water Resources and U. S. Geological Survey releveled a number of level lines in the vicinity of Lake Oroville, extending south as far as the town of Wyandotte. Bench marks surveyed in the Oroville area are shown on Figure 43. This survey work showed the ground elevation had lowered in some areas since previous third-order surveys dating back to the 1940s. This lowering, or sag, was found in an area north of the Cleveland Hill crack zone.

Within a week after the earthquake, the U. S. Geological Survey installed five special arrays of survey monuments along the crack zone at Cleveland Hill to monitor movement in the immediate vicinity of the crack zone. The USGS surveys of these monuments showed that, for some time after the earthquake, the west side of the crack zone moved downward and the horizontal distance lengthened in an east-west direction across the crack. These measurements suggest normal fault movement resulting from eastward extension.

When it became known in October 1975, that cracking was progressing northward, additional level lines were established by the Department of Water Resources across the crack zone on Mission Olive Road, and a new level line brought south to cross the Cleveland Hill crack zone. Releveling along both Mission Olive Road and across the Cleveland Hill zone indicated the west side of the fault continued to drop.

Because the cracking was trending towards the Bidwell Canyon arm of Lake Oroville, leveling was done along the Bidwell Canyon Saddle Dam. The results of these surveys are shown in Figure 42. The two drops in the elevation profiles near bench marks BB-2 and BB-8 probably show normal settlement of embankment at places of maximum embankment height, rather than crustal movement. For the rest of the monuments, with some on original ground, most of the change in elevation since the 1969 survey is assumed to be due to minor crustal movements continuing after the Oroville earthquake. Elevations are about 10 millimetres (0.40 inch) lower on the west side of the dam, indicating a westerly tilt, or lowering to the west. The 1969 survey also indicated this trend.

Four shears exposed by the foundation excavation are also shown in Figure 42. None are believed to be the fault along which ground cracking occurred, but this is not certain, because the fault location in the vicinity of Bidwell Canyon Saddle Dam is not known precisely. The fault is believed to be west of the dam.

By October 1975, geodetic data indicated that the block west of the fault zone had dropped down and that the movement was still continuing. The geodetic work was corroborated further by visual evidence, for the cracks along the Cleveland Hill Fault were even wider and cracks were breaking new ground to the north. Another level line was extended southward to the vicinity of Bangor to measure elevation changes along the southeastern projection of the fault zone. This southerly level line has been surveyed only once, so it is not possible yet to determine whether measurable movement is occurring to the south of Cleveland Hill.

The settlement contours shown on

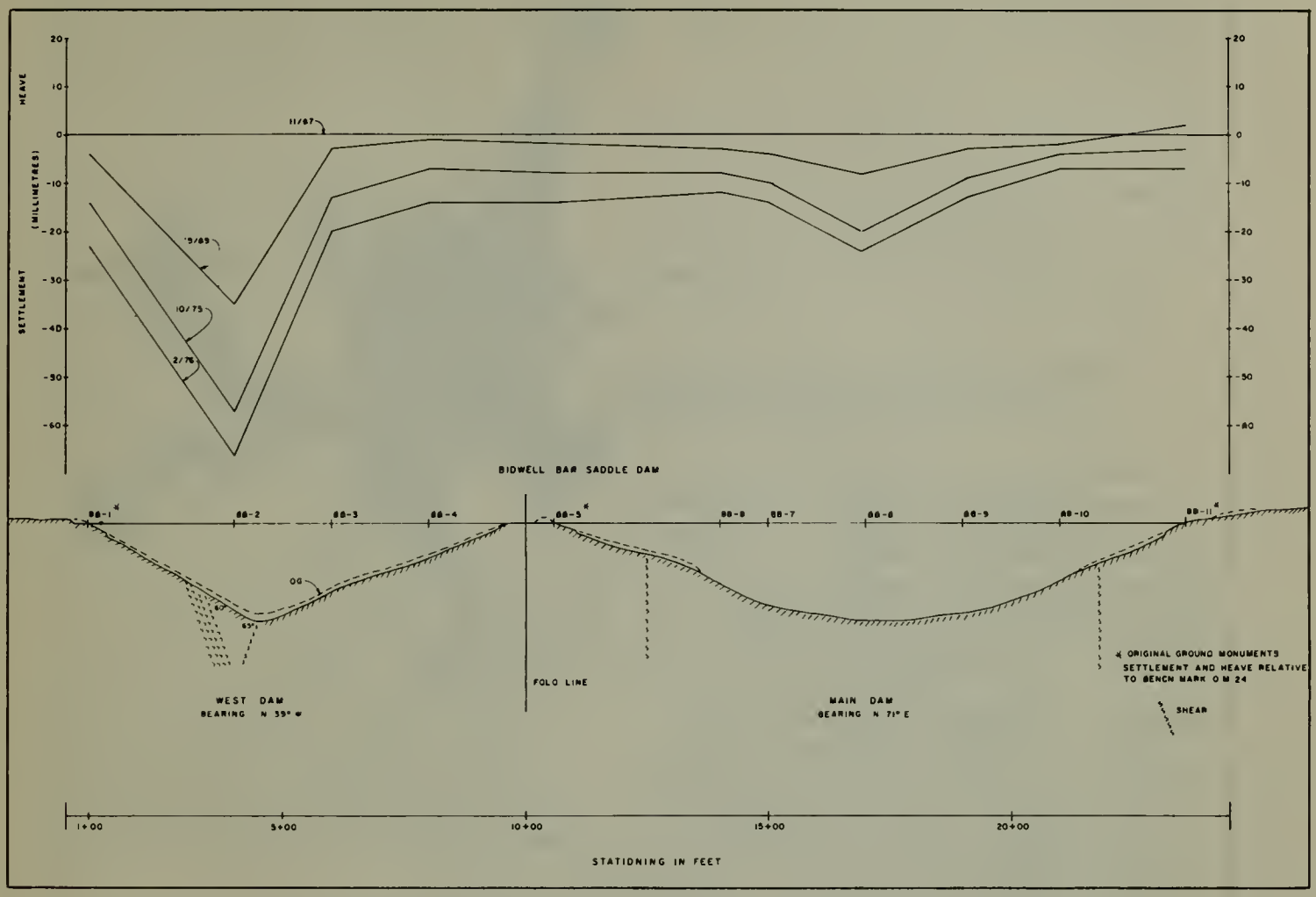


Figure 42. Changes in Crest Elevation of Bidwell Bar Saddle Dam between November 1962 and February 1976

Figure 43 are a computer plot of changes in ground elevations between postearthquake surveys in August 1975 and in February 1976. They do not show any settlement which may have occurred during the August 1, earthquake and the early aftershock period. For these computations Bench Mark No. OM-24, the easternmost bench mark shown on Figure 43, was used as a base elevation and presumed to have remained unchanged. Surveys extended east from OM-24 to known stable bench marks validate the assumption that Bench Mark OM-24 is stable.

The settlement contours shown on Figure 43 show a general lowering of ground elevation west of a north-trending zone that coincides approximately with the Cleveland Hill Fault and the associated Swain Ravine lineament. Maximum settlement of 30 millimetres (1.2 inches) occurred in depressed areas west of the Cleveland Hill Fault and also north of Oroville Dam. Settlement of the Oroville Dam foundation was about 15 millimetres (0.6 inch).

It should be noted from the settlement contours that the postearthquake settlement seems to form a broad, poorly defined trough with a bottom width of about 3 kilometres (1.9 miles). This trough, or depression, has a northerly trend and is bordered on the east by the zones of ground cracking. Surveys

Figure 43. Changes in Ground Elevations in Oroville Area, August 1975 to February 1976

extended west of the depression indicate that settlement diminishes westward and approaches zero in the vicinity of Richvale, 16 kilometres (10 miles) west of Oroville.

The present plan is to relevel the main level lines during the summer of 1977. If considerable movements are still being detected by the leveling program, surveys will be continued at approximately six-month intervals. The leveling across Bidwell Canyon Saddle Dam, which shows some partially explained anomalies at the original ground monuments, will also be continued at approximately six-month intervals.

1940 Magnitude 5.7 Earthquake

The Oroville area has generally been considered to be a region of relatively low seismic activity. Prior to 1975, however, 58 earthquakes were recorded with a 60-kilometre (37-mile) radius of Oroville damsite. This record includes only the larger or more recent shocks, because prior to the 1940s, only a few seismograph stations had been established in the Oroville area.

On February 8, 1940, an earthquake of magnitude 5.7 occurred north of Oroville. The earthquake hypocenter was originally calculated to be 28 kilometres (17 miles) northeast of Oroville damsite at a depth of 35 kilometres (22 miles). The seismographs for this earthquake were recently reevaluated by the University of California Seismological Laboratory, using more precise methods than were available 30 years ago. The new calculations shifted the earthquake hypocenter 40 kilometres (25 miles) northwest of the original location or 50 kilometres (31 miles) north of Oroville damsite, at a depth of 20 kilometres (12 miles) (Figure 44). However, no fault has yet been identified as a source for the 1940 earthquake.

In an attempt to correlate the 1940 earthquake to faulting in the area, remote imagery was inspected for lineaments and the lineaments were plotted on topographic base maps. These lineaments are summarized on Figure 44. A preliminary field check of some of the more prominent lineaments proved inconclusive. Extensive additional geologic field study will be necessary to reveal the faults in the area so that the source of the 1940 earthquake can be determined.

Trenching Along Lineaments Between Cleveland Hill Crack Zone and Oroville Reservoir

In May 1976, the Department of Water Resources excavated and logged seven additional exploration trenches (Figure 45). These trenches were excavated across several lineaments which had been mapped northward from the Cleveland Hill and Mission Olive crack zones area to the Bidwell Bar arm of Lake Oroville.

Locations of the lineaments and trench sites are shown on Figure 30. Geologic logs of the trenches are included as Figures 46 through 54. The purpose of the trenches was to determine if any of these lineaments reflected the surface traces of throughgoing faults extending northward from the crack zone to Lake Oroville.

In three trenches (Nos. 5, 7A, and 8), faults that correlated well with surface cracks or lineaments or both were observed. No faults were found in the remaining four trenches.

In Trenches Nos. 5 and 7A, the faults exposed were in the metavolcanic bedrock (Figures 55 and 56). No evidence of movement on these faults as a result of the 1975 Oroville earthquake was detected and no offset of the soil-bedrock contact was apparent.

Trench No. 8 was excavated in alluvium to a depth of 3.9 metres (12.8 feet). The lower 0.5 metre (1.6 feet) of alluvium consisted of permeable

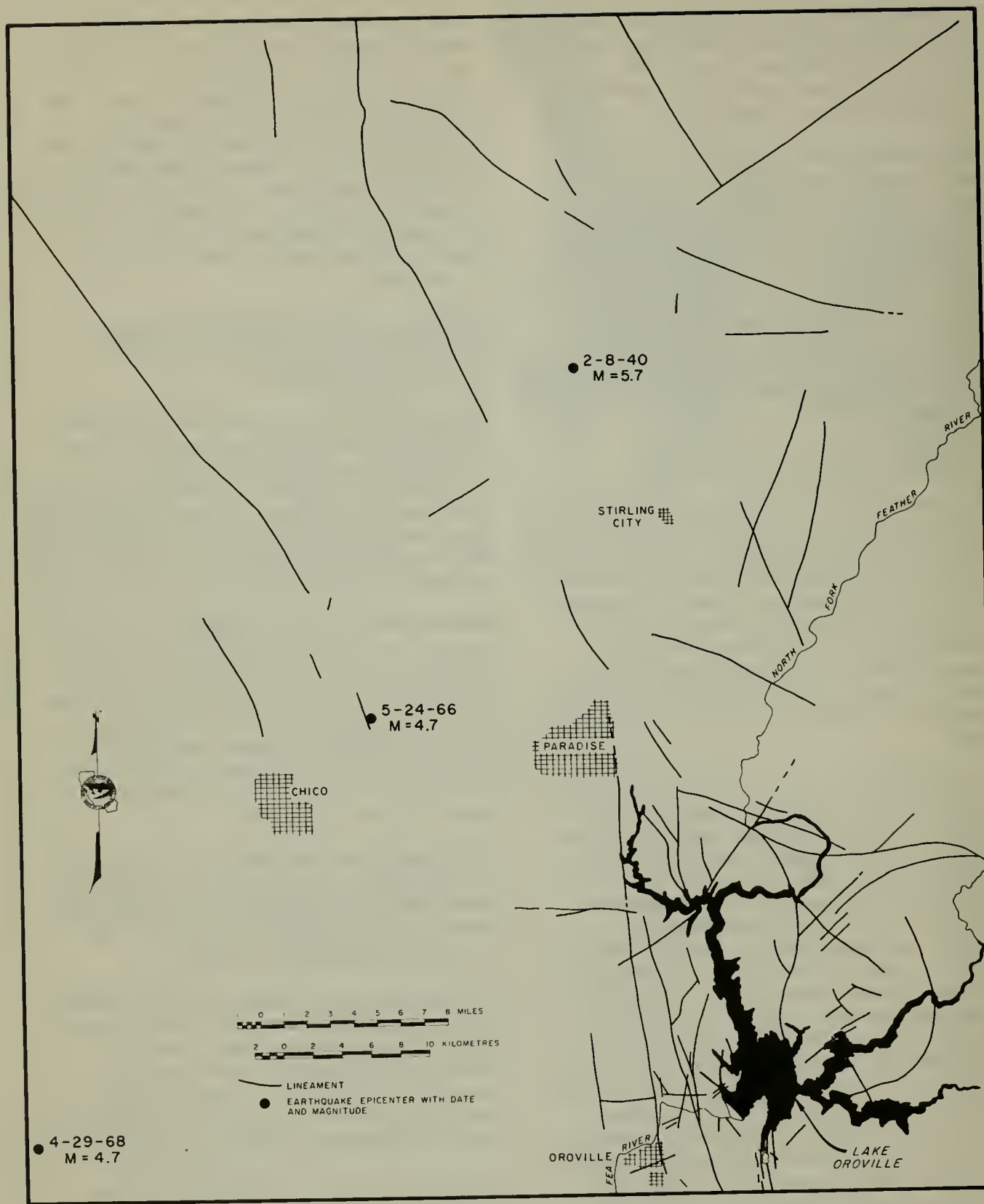


Figure 44. Lacotian of 1940 Magnitude 5.7 and 1966 and 1968 Magnitude 4.7 Earthquakes, and Lineaments North of Lake Oroville

Figure 45. Trench 10, View Looking West

gravel having a relatively distinct and regular contact with an overlying sandy silt. Evidence of faulting was a narrow, steeply dipping disrupted zone in the gravels, across which there was an apparent vertical offset of the gravel-sandy silt contact of 30 millimetres (1.2 inches), with the west side down relative to the east side (Figure 57). The disturbed zone in the gravels appears to be the result of recent fault movement, but the vertical offset probably occurred prior to the 1975 Oroville events -- since no vertical offset was observed on the cracks overlying the fault at the ground surface. This means small fault displacements probably occurred prior to the filling of Lake Oroville.

Three additional trenches (Nos. 12, 13, and 14) were excavated by Department of Water Resources in October and November 1976. Trenches Nos. 12 and 13 exposed apparent bedrock faults; no fault was exposed in Trench No. 14. Locations of the trench sites are shown on Figure 30.

The trenching done thus far by the Department of Water Resources and others has demonstrated that linear zones of surface cracking related to the Oroville earthquake and aftershocks coincide with a preexisting fault or fault zone. In some instances, trenches dug across extensions of the lineaments along which the surface cracking occurred exposed faults correlating well with the mapped lineaments. In other instances, trenches in the lineaments exposed no significant structural or geologic features to account for the mapped lineament.

In general, the faults observed in the trenches appeared to be much smaller than would be expected from the prominence and extent of the lineaments. Answers to the questions regarding the northward extent and continuity of the faults underlying the Cleveland Hill and Mission Olive crack zones require additional exploration, and conclusive answers may not be obtainable.

Trenching By Other Organizations

In January 1976, Woodward-Clyde Consultants excavated three exploration trenches across the Cleveland Hill and Mission Olive crack zones. The trenches were excavated under contract with the U. S. Army Corps of Engineers as part of a study to evaluate the potential for earthquakes and surface faulting at their Parks Bar Afterbay Dam site. The Afterbay Dam site is on the Yuba River about 28 kilometres (17 miles) south-southeast of the trench locations.

All three exploration trenches exposed a preexisting bedrock fault closely related to the ground surface cracking. According to Woodward-Clyde Consultants, interpretation of the trenches indicates recurrent late Quaternary displacement on the Cleveland Hill Fault, with a total vertical displacement of 46 centimetres (18 inches) in the soil profile resulting from three or more episodes of faulting. They further state "...fault

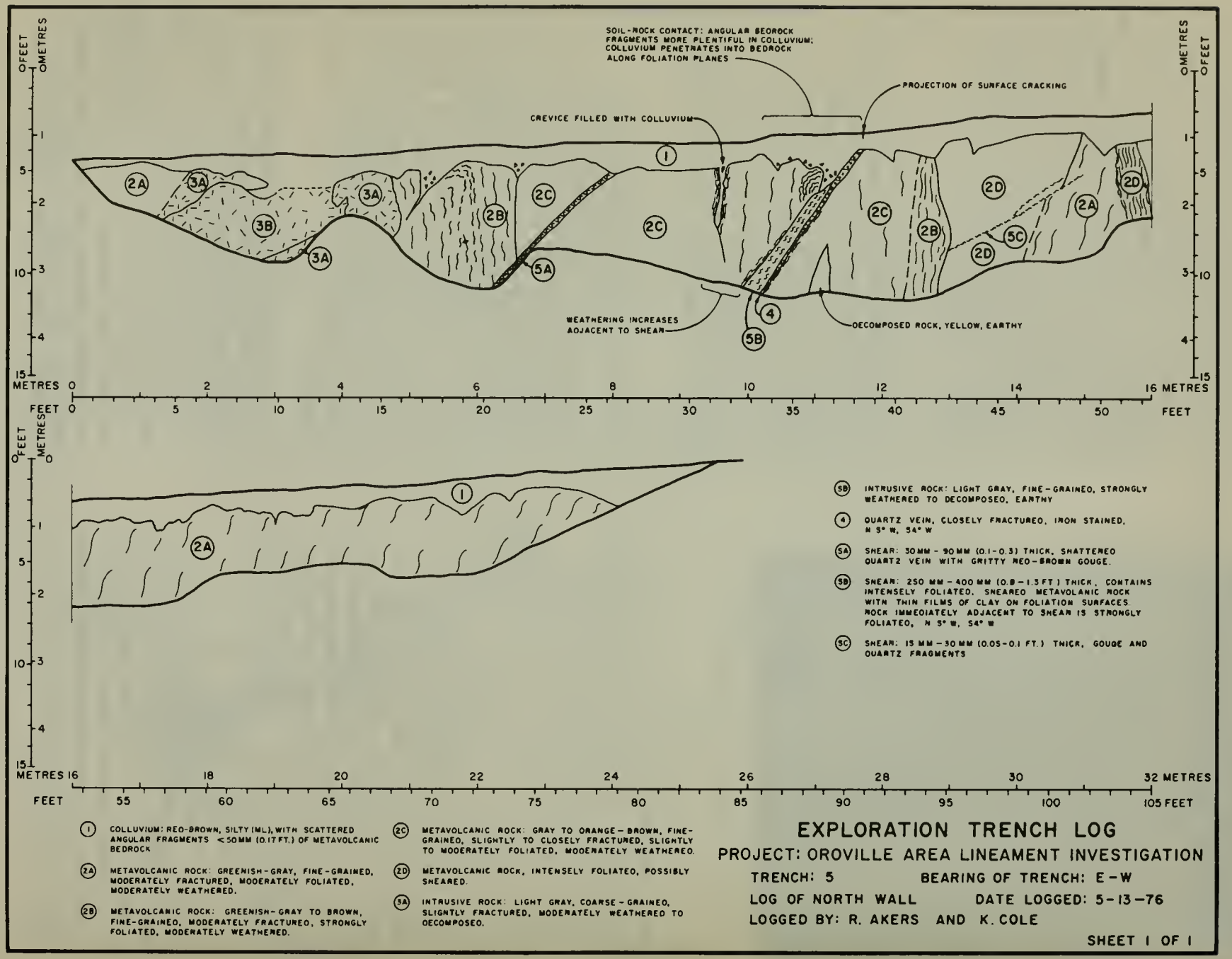


Figure 46. Trench 5

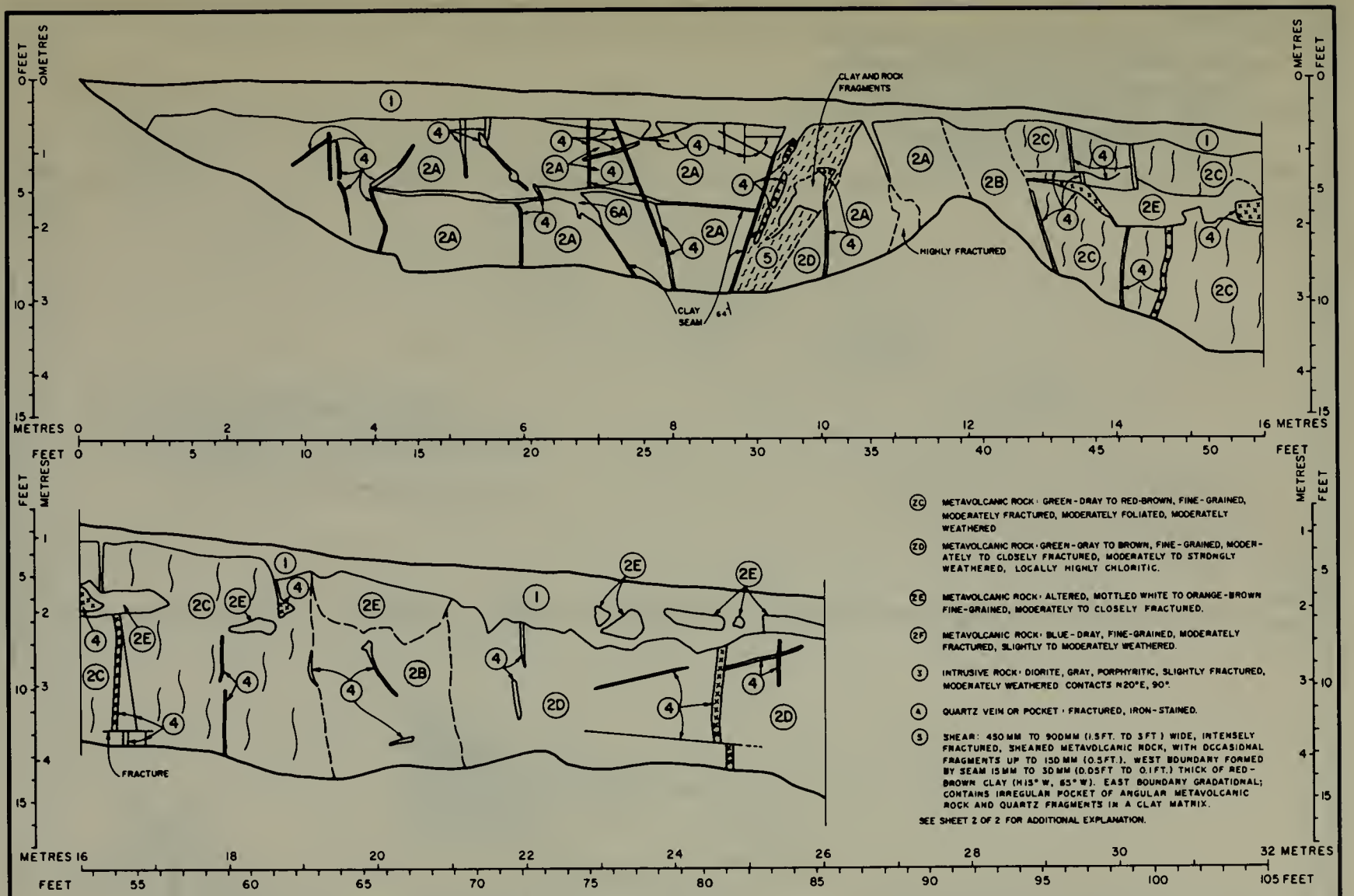
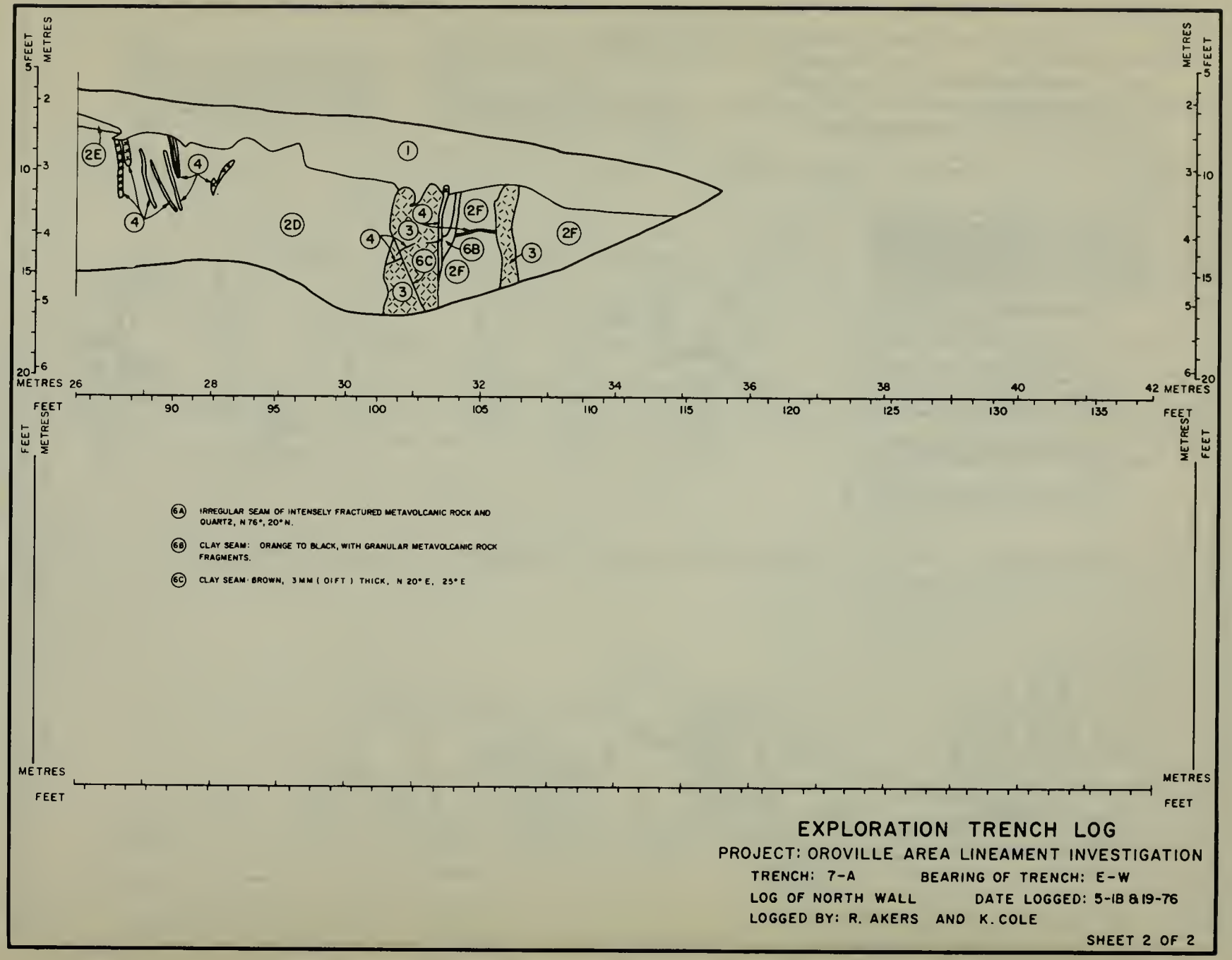


Figure 47. Tench 7A (1 of 2)



EXPLORATION TRENCH LOG

PROJECT: OROVILLE AREA LINEAMENT INVESTIGATION

TRENCH: 7-A BEARING OF TRENCH: E-W

LOG OF NORTH WALL DATE LOGGED: 5-18 & 19-76

LOGGED BY: R. AKERS AND K. COLE

SHEET 2 OF 2

Figure 48. Trench 7A (2 of 2)

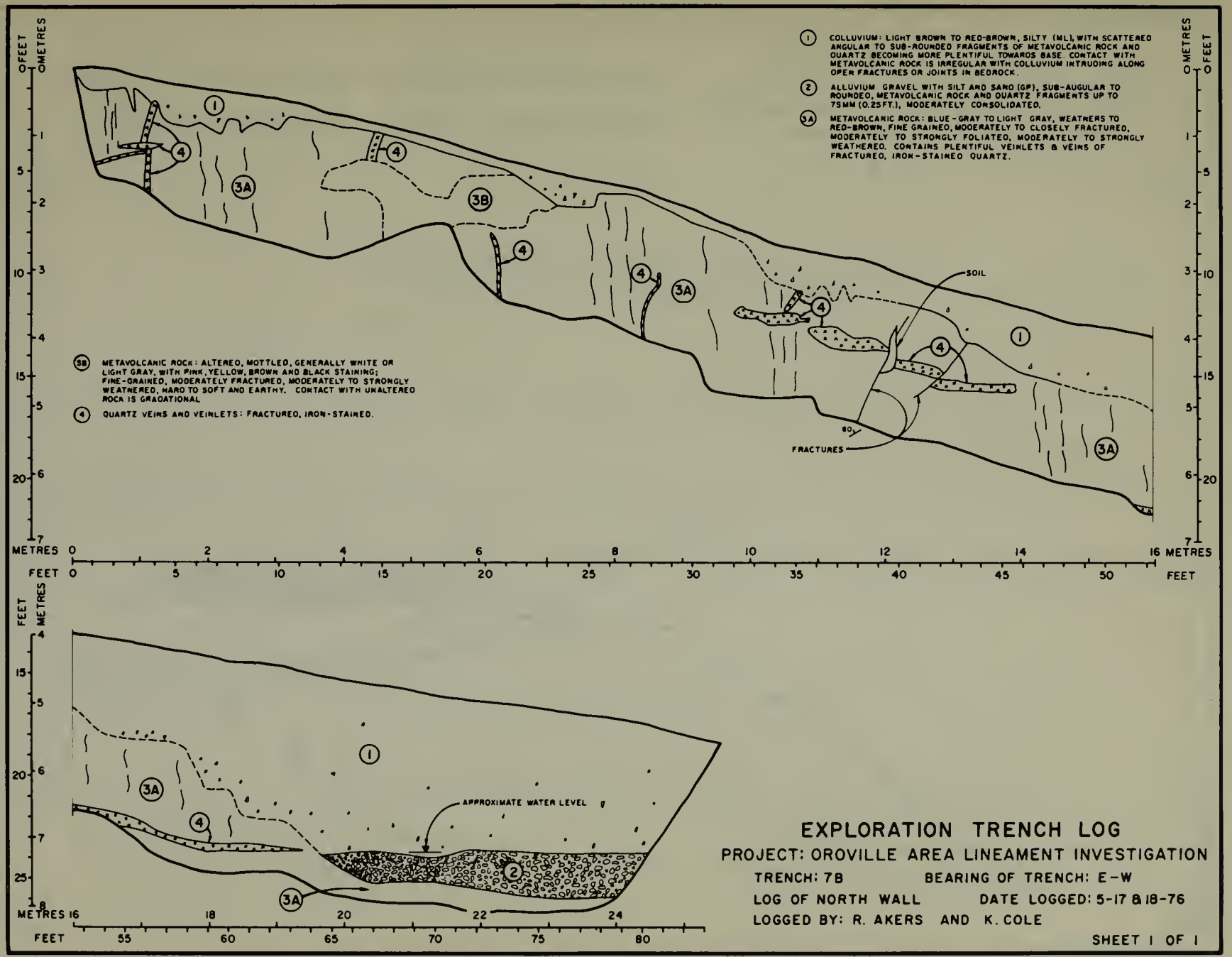


Figure 49. Trench 7B

EXPLORATION TRENCH LOG

PROJECT: OROVILLE AREA LINEAMENT INVESTIGATION

TRENCH: 7B BEARING OF TRENCH: E-W

LOG OF NORTH WALL DATE LOGGED: 5-17 & 18-76

LOGGED BY: R. AKERS AND K. COLE

SHEET 1 OF 1

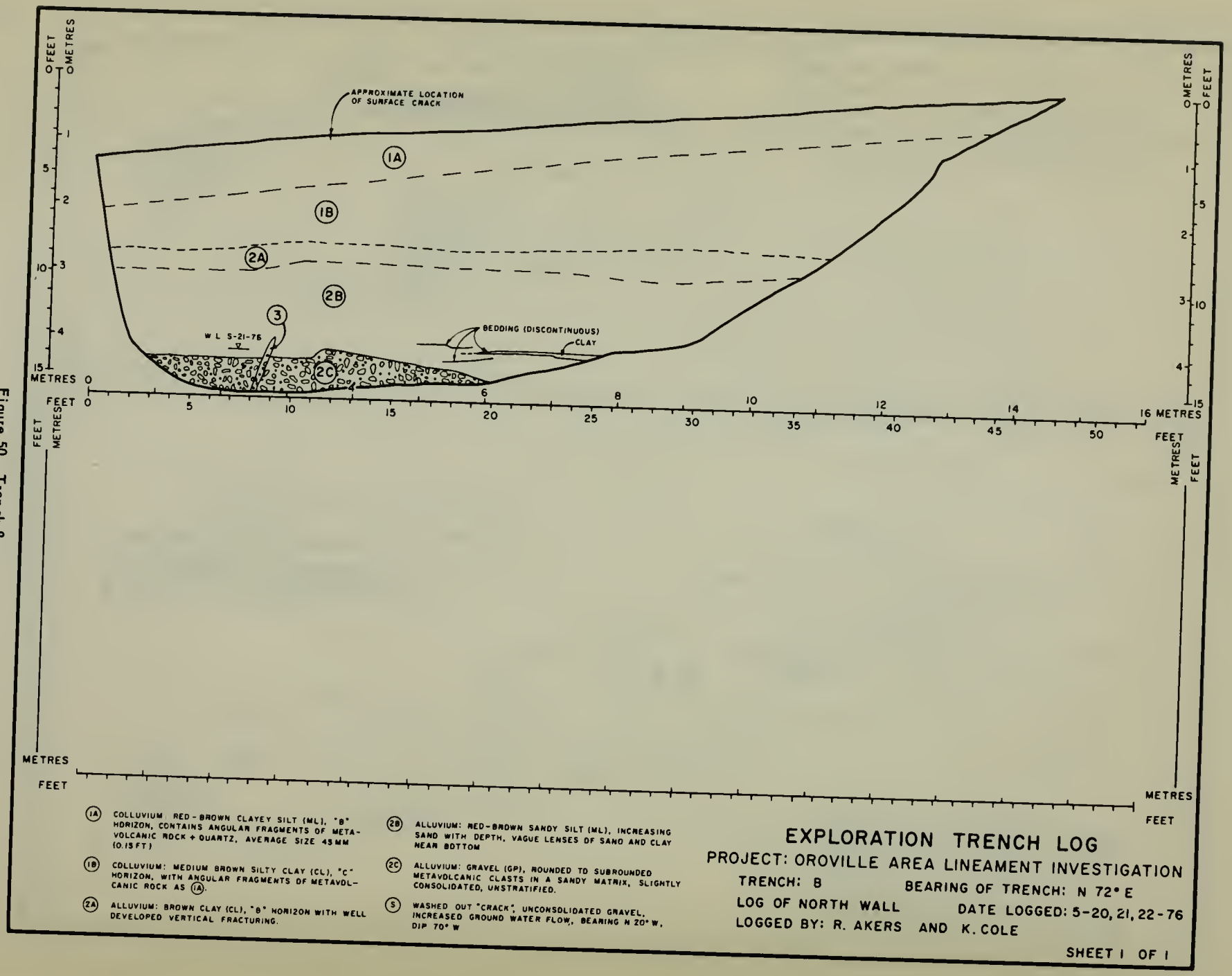


Figure 50. Trench 8

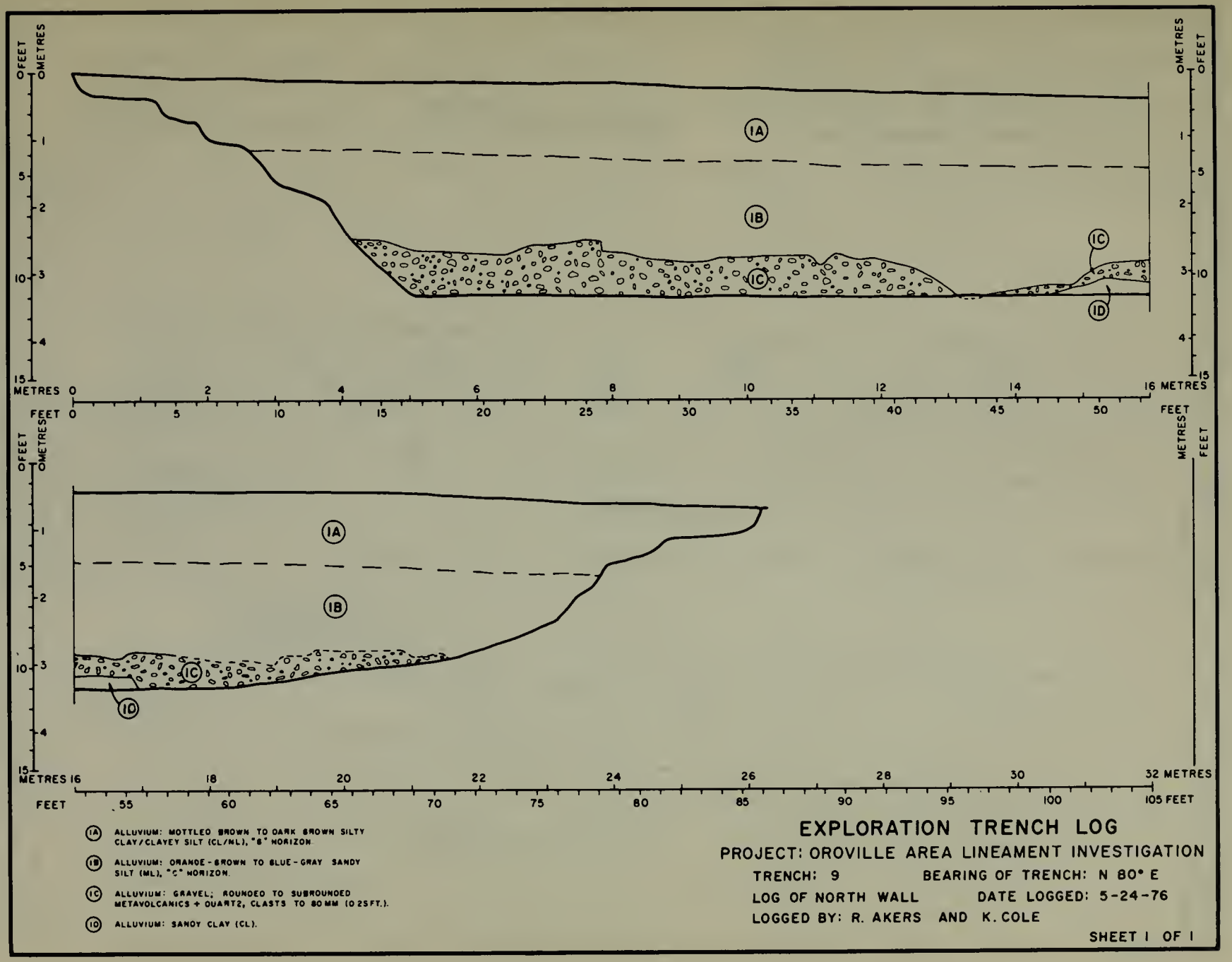


Figure 51. Trench 9

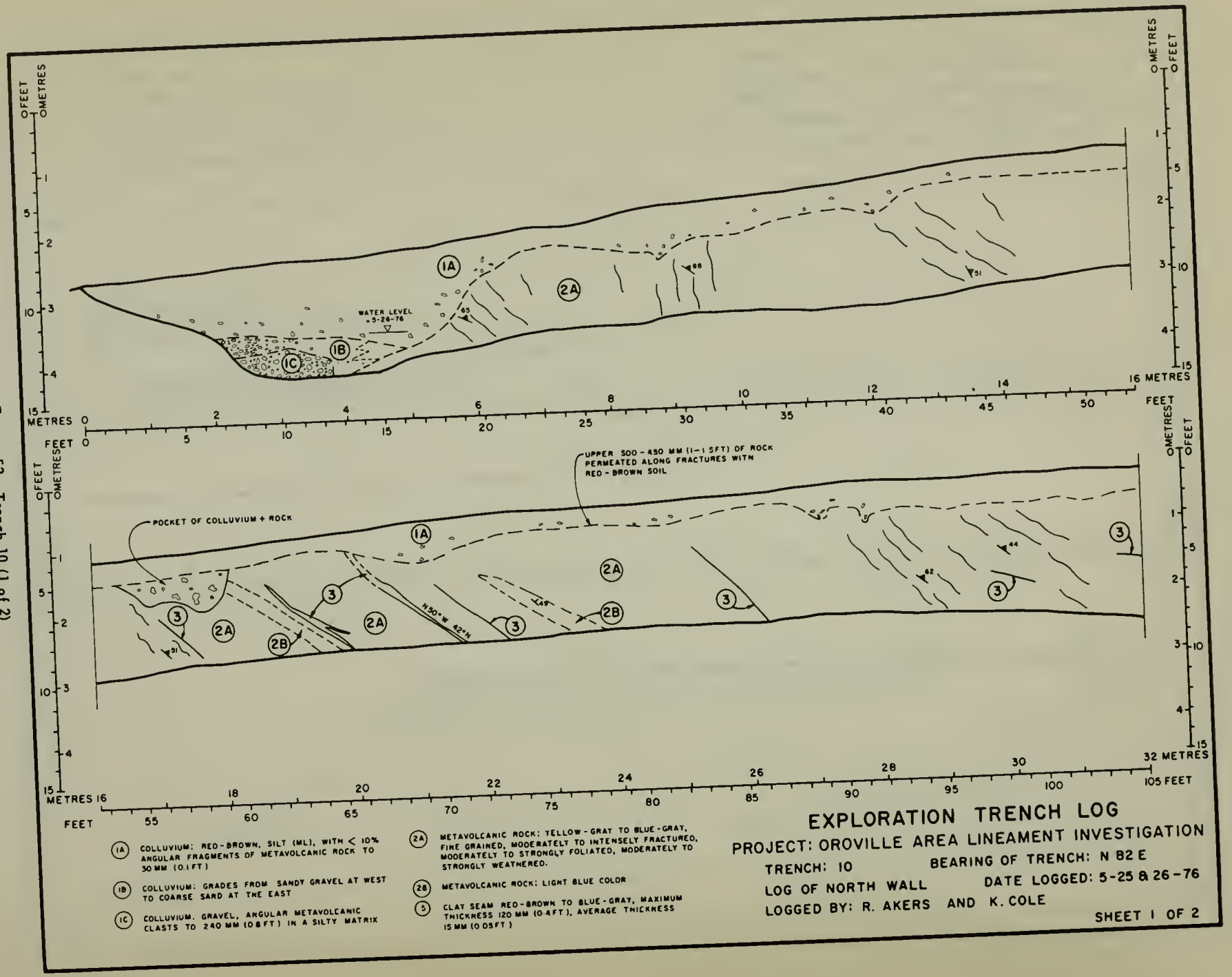


Figure 52. Trench 10 (1 of 2)

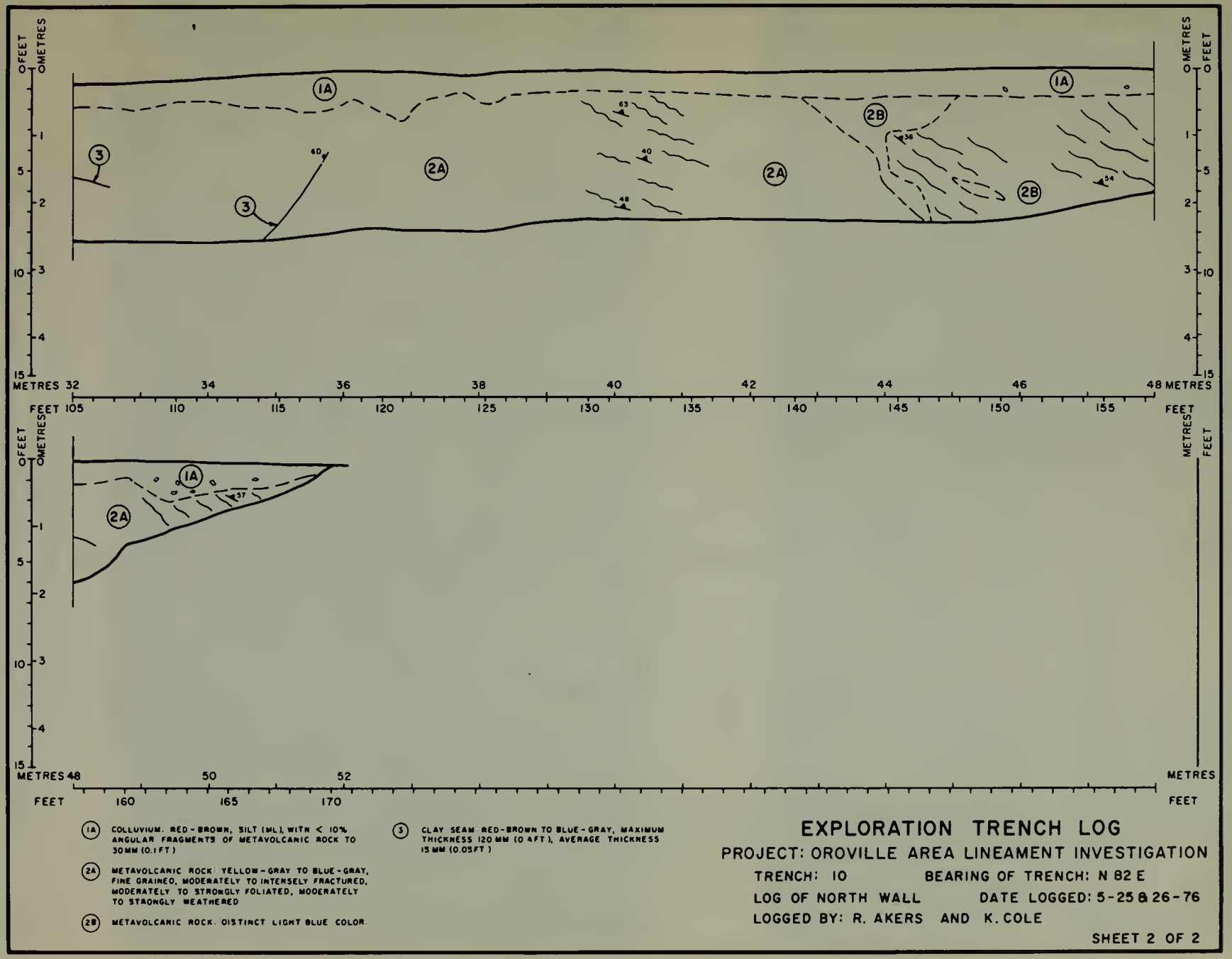


Figure 53. Trench 10 (2 of 2)

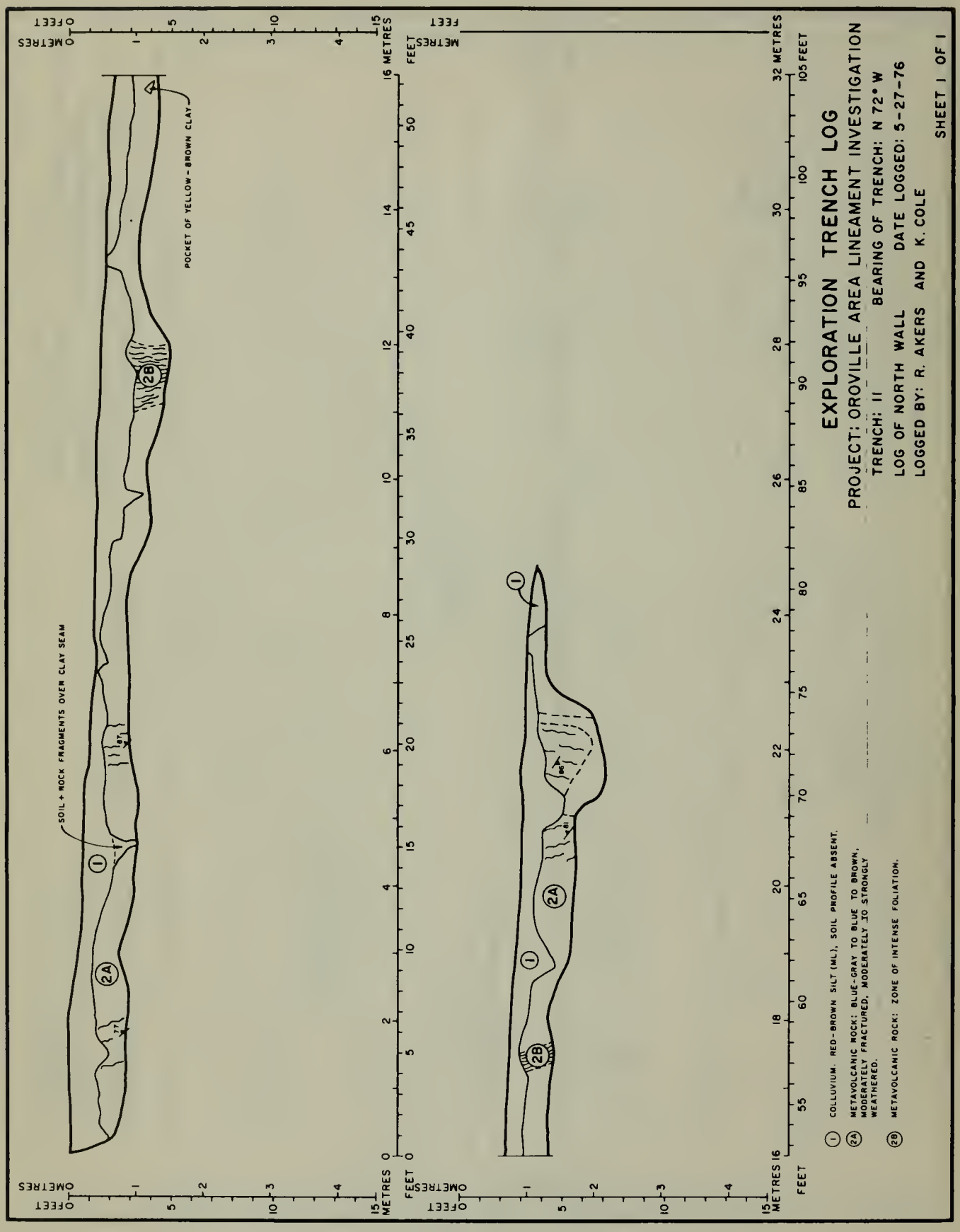


Figure 54. Trench 11

Figure 55. Beginning Excavation of Trench 5 at North End of West Crack

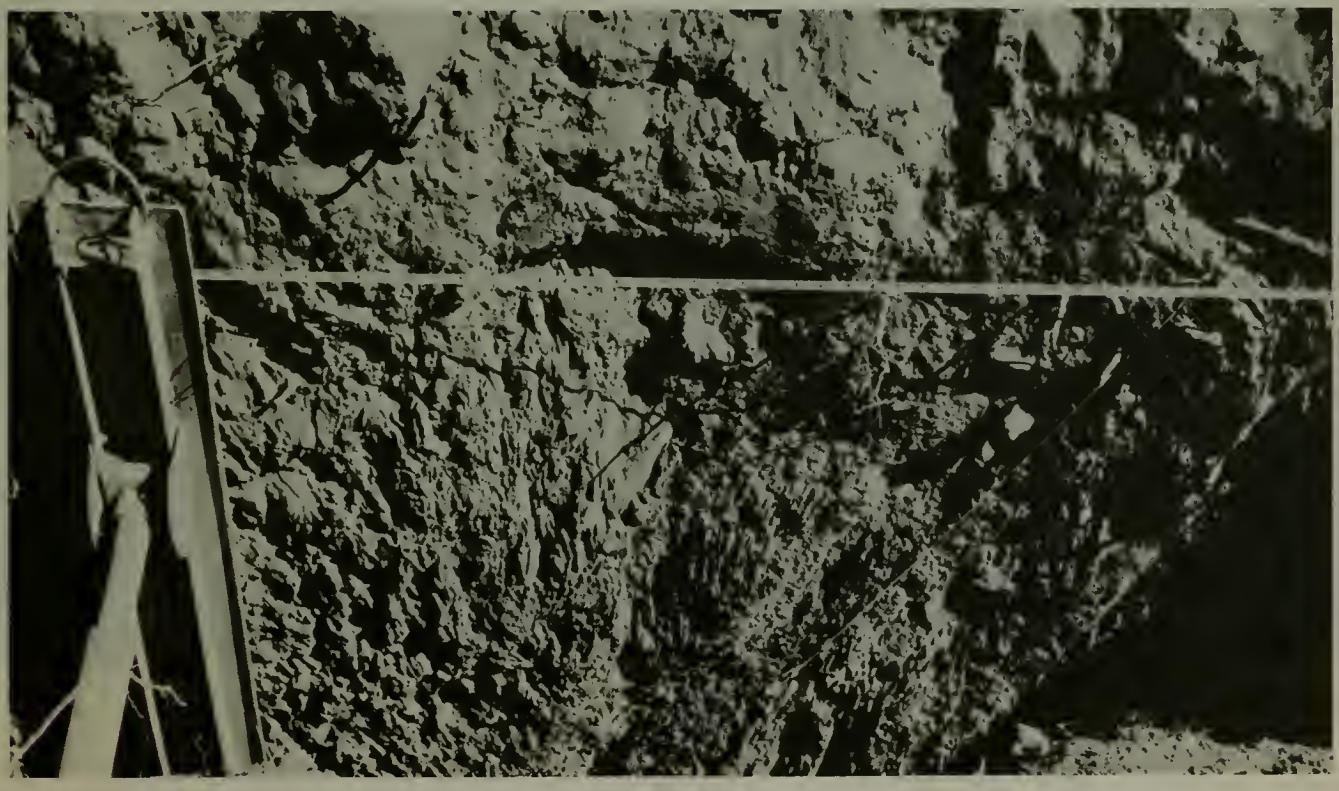


Figure 56. Portion of north wall of Trench 5. Fault marked by string in right side of photograph coincides with northward projection of surface cracks.

Figure 57. Foult in south wall of Trench 8. Foult consists of 8 centimetres (3 inches) zone of disturbed soil moterials which were eroded out by ground water flowing into trench. String neor center of photograph is horizontol. Alluvium-colluvium contact, marked by mails, offset obout 5 centimetres (1.8 inches) ocross zone, with west (right) side down relative to eost side.

displacement, as observed in the exploratory trenches, strongly suggests that earthquakes of magnitude 6 to 6-1/2 could have occurred and the maximum vertical displacement in a single event could have been 3 to 6 inches".

The Corps of Engineers continued their study of the Parks Bar Afterbay Dam site by excavating five additional trenches in the vicinity of the damsite. The trenches were excavated across the Swain Ravine lineament at locations from 1.5 to 7 kilometres (1 to 4 miles) north of the Yuba River. In four of the trenches, bedrock faults and sheared bedrock were exposed. None of the bedrock structures could be found to penetrate the soil or surficial materials, and no evidence of recent movement was noted. No evidence of faulting or shearing was observed in the remaining trench.

Woodward-Clyde Consultants is also engaged in a study of the Foothill Fault System for the Pacific Gas and Electric Company. As part of this study, they have excavated exploration trenches at nine sites along the lineament trend, extending from the Cleveland Hill area to the Yuba River. Four of these sites crossed the Cleveland Hill and Mission Olive crack zones and produced results similar to those encountered in the trenches previously excavated for the Corps of Engineers.

Trenches at the other five sites were designed to cross the Paynes Peak lineament, the Swain Ravine lineament, or the Prairie Creek lineament. At four of the sites, bedrock structures interpreted as shears or faults were exposed in the trenches. None of these structures extended upwards into the overlying alluvium or colluvium, and no indication of recent movement was noted. At the remaining site, no structure identified as a fault or shear was observed.

Old Fault Zones

The work of the U. S. Army Corps of Engineers, Woodward-Clyde Consultants, and Department of Water Resources north of the Yuba River reveals geologic structures not previously mapped in the western metamorphic belt of the Sierra Nevada. The Prairie Creek, Swain Ravine, and Paynes Peak (Figure 58) are three strong lineaments that appear to result from geologic structure. In the field, these lineaments follow in well-defined valleys throughout most of the study area, and they can be seen on topographic maps almost as well as on the LANDSAT, SLAR, AND IR color imagery.

There are intervals along the lineaments where they are not clearly visible, either on imagery or in the field. The Cleveland Hill crack zone is one such poorly defined area along the Swain Ravine lineament. However, because lineaments continue north and south of the poorly defined zones, they are assumed to be discontinuous surface manifestations of throughgoing, continuous geologic structures.

In the field, the lineaments have the appearance of fault zones, primarily because they follow linear valleys and cross saddles, and because occassional seeps and springs are found along them. Exposures of faults are rare, however, and the faults which are seen seem too small for the fault-like topographic features surrounding them. Rocks adjacent to the lineament zones frequently are strongly foliated. In the Oroville area, this foliation usually has a northerly strike and nearly vertical dip.

Trenching by the Department of Water Resources, the Corps of Engineers, and Woodward-Clyde Consultants in these zones usually revealed a fault or faults and/or broken rock. Well-defined fault planes were usually thin, although zones of broken rocks interpreted as fault zone extend several tens of feet in some trenches.

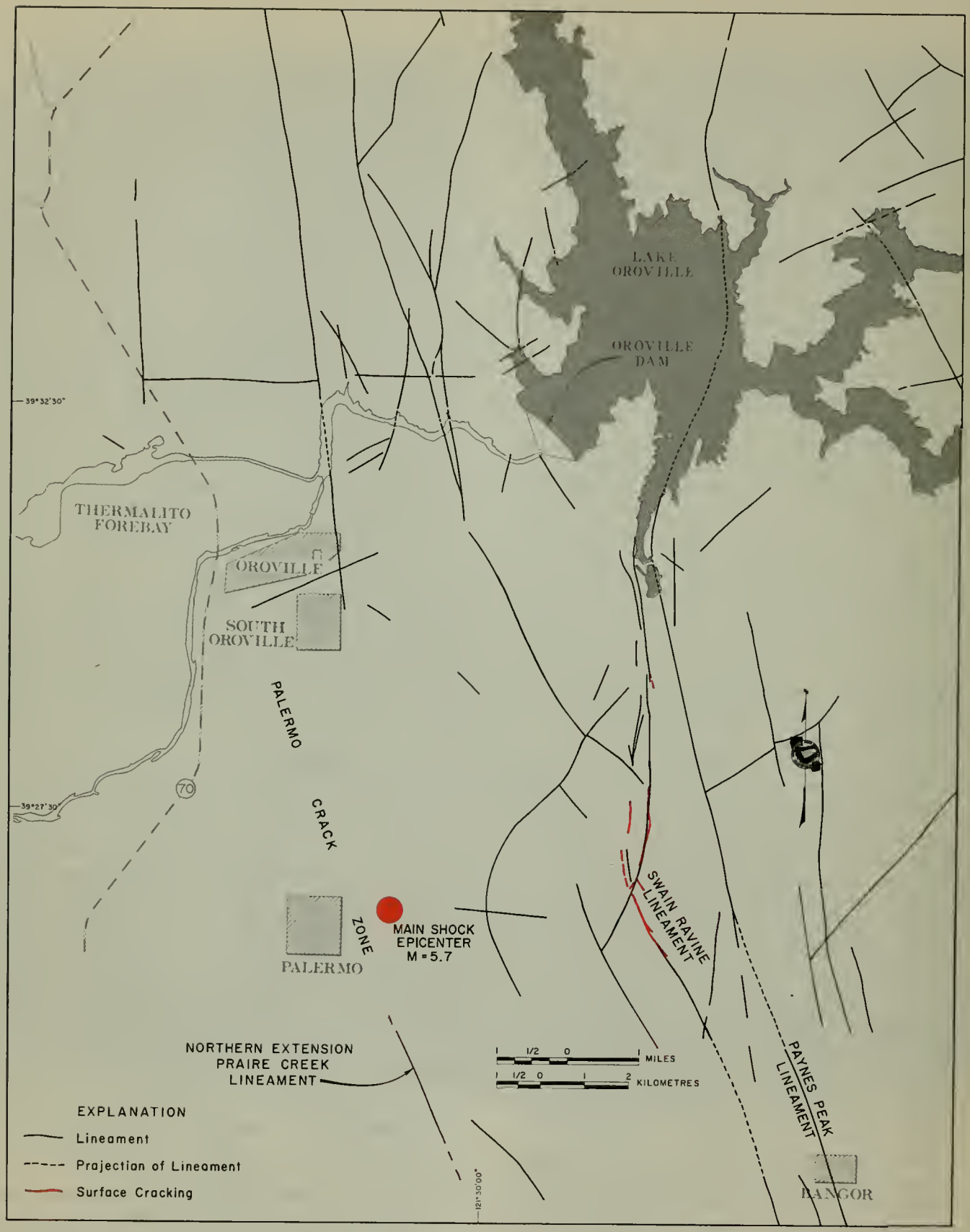


Figure 58. Lineaments south of Lake Oroville, including Prairie Creek, Swain Ravine, and Paynes Peak, the three main lineaments

Most of the exploratory trenching was done along the Swain Ravine lineament, because it was along this lineament that the ground cracking progressed northward toward Lake Oroville. A total of 30 trenches were excavated by various investigators along the three major lineaments north of the Yuba River. Of these, 26 trenches were on the Swain Ravine lineament, two on the Prairie Creek lineament, and two on the Paynes Peak lineament. Faults were exposed in all but seven of the trenches. Displacement of features in either the soil profile or the soil-bedrock contact were found in 14 trenches along the Swain Ravine lineament, indicating fault movement occurred after the soil cover developed. Age of the soil formed upon the metamorphic rocks in the study area is not known; however, the soil appears young, and those who have worked with paleosols in nearby areas speculate ages ranging from 10,000 to 25,000 years ago. The following tabulation summarizes the results of the trenching.

RESULTS OF TRENCHING ALONG LINEAMENTS
NORTH OF YUBA RIVER

SWAIN RAVINE LINEAMENT AND CRACK ZONES

TRENCHES LISTED FROM NORTH TO SOUTH	EXPOSED FAULTS	EVIDENCE OF RECENT MOVEMENT	COMMENTS
DWR 11	No	--	Anomalous Foliation
DWR 10	No	--	
DWR 13	Yes	Yes	
DWR 14	No	--	
DWR 12	Yes	Yes	15-30mm offset in gravel
DWR 8	Yes	Yes	
DWR 9	No	--	
DWR 7A	Yes	No	
DWR 7B	No	--	
DWR 5	Yes	No	
PG&E-WCC GRUBBS 2	Yes	Yes	
USCE-WCC GRUBBS 1	Yes	Yes	
PG&E- WCC SIMS 1	Yes	Yes	
USCE-WCC CLEVELAND HILL 2	Yes	Yes	
USCE-WCC CLEVELAND HILL 1	Yes	Yes	
PG&E-WCC LORRAINE 1,2,&3	Yes	Yes	
DWR-A	Yes	Yes	
DWR-B	Yes	Yes	
PG&E-WCC CLEVELAND HILL 3	Yes	Yes	
DWR-D	Yes	Yes	
USBR-WCC ORANGE AVE A thru H	Yes	Yes	
PG&E-WCC PACE 1 thru 5	Yes	No	
USCE 4F-1	Yes	No	
" 4F-2	No	--	
" 4F-3 & 4	Yes	No	
" 4F-5	Yes	No	
PAYNES PEAK LINEAMENT			
PG&E-WCC KNAPP 1	No	--	
PG&E-WCC BURT 1 & 2	Yes	No	
PRAIRIE CREEK LINEAMENT			
PG&E -WCC O'BRIEN 1	Yes	No	
PG&E-WCC WILSON 1	Yes	No	

Displacements in the soil zone were seen only in trenches along the Swain Ravine lineament between Lake Oroville and the vicinity of the village of Bangor. This indicates that part of the zone of faulting in the Swain Ravine lineament has been active during the recent geologic past. It is also possible that undetected displacements have occurred along more of the lineament. The evidence seems clear, however, that recent movement occurred along faults in the Swain Ravine lineament some distance south of Lake Oroville prior to the existence of the lake.

Although studies of lineament zones are incomplete, it is presumed that the three main lineaments probably are old Mesozoic Fault zones and represent the imprint of an earlier tectonic regional style -- the mark of a regional pattern of tectonic stresses different from those present today. The trenching indicates that these old fault zones consist of broken rock interlaced with smaller faults. Because they are zones of sheared rock, these old fault zones probably are zones of weakness, along which adjustments to present-day tectonic stresses are prone to occur.

Some minor movements or adjustments have taken place along faults in the Swain Ravine lineament during recent geologic times, and small movements may have occurred elsewhere but remain undetected. Recent movements have occurred at a slow rate, certainly slower than geomorphic processes obliterating geologic evidence of fault movement; otherwise there would be more field evidence of recent fault movements.

The Swain Ravine and Paynes Peak lineaments appear to extend into the Bidwell Bar arm of Lake Oroville, although the precise location of their entry into the lake has not been determined yet by the investigations. Where the zones go north of the lake is not known at this stage of investigation, but they may merge in the lake area, come out to the north in Canyon Creek, and continue north until truncated by the Big Bend Fault.

The Prairie Creek zone coincides with the "Palermo Crack Zone" and lines up with faulting in the Pliocene Tuscan Formation northwest of Oroville. The spatial relationship of the Prairie Creek lineament to the "Palermo Crack Zone" and to faulting in the Tuscan Formation to the north suggests the Prairie Creek Zone may be a throughgoing feature of considerable linear extent along which post-Pliocene Fault movement has occurred. In any event, the northwestern extension of the Prairie Creek lineament warrants further investigation.

Results of Investigation

Summary of Geologic Findings

Ground cracking occurred at Cleveland Hill along a previously unmapped old fault zone in metavolcanic rocks in the metamorphic belt of the western Sierra foothills. This fault zone is in the Swain Ravine lineament, which strikes in a generally northerly direction and appears to pass through, or near, the Bidwell arm of Lake Oroville. The fault zone is believed to dip west approximately 60 degrees. It is assumed that the fault along which the cracking occurred is the fault, or one in a system of faults, responsible for the August 1, 1975, Oroville earthquake.

As time passed, ground cracking progressed farther northward along the fault zone, and the original cracking at Cleveland Hill widened and appeared to drop down on the west. It is assumed that the postearthquake ground cracking is caused by a lag in strain adjustments being propagated to the surface updip along the fault system from the main shock hypocentral area.

Geodetic data indicate that the ground

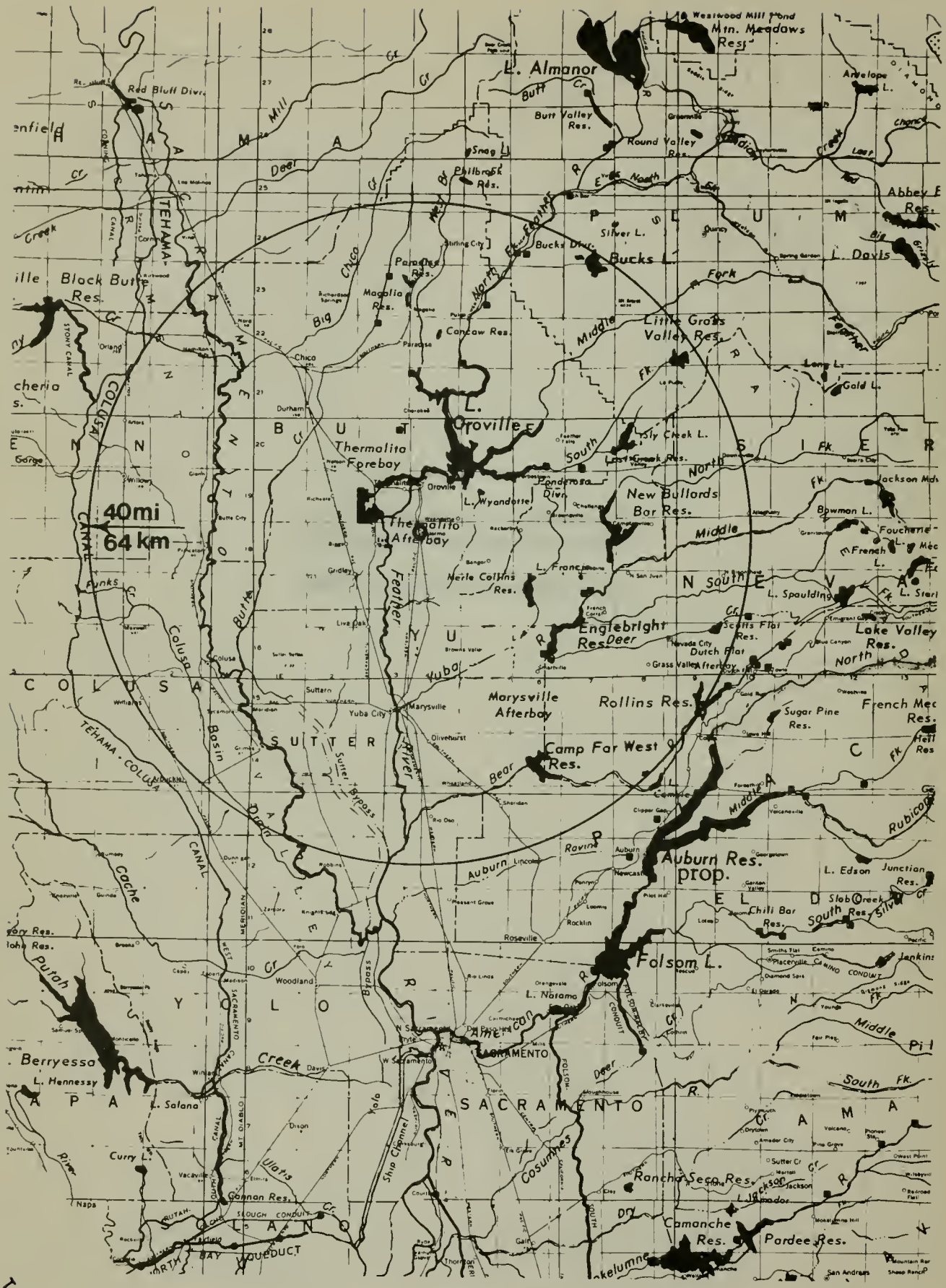
levels west of the fault zone dropped downward. The USGS arrays at Cleveland Hill also show east-west extension across the crack zone. In short, the type of strain measured suggests normal faulting along a north-striking fault system caused by regional east-west extension. Ground elevations continued to change after the earthquake, and still may be changing.

Three prominent lineaments stand out from the numerous lineaments detected in various kinds of imagery. These three are called the Prairie Creek, Swain Ravine, and Paynes Peak lineaments. All of the ground cracking was along the Swain Ravine lineament. Trenching along these lineaments revealed faults. Trenches along the Swain Ravine lineament between Lake Oroville and Bangor indicate small fault movements have occurred during recent geologic times.

PART 2

EVALUATION OF DAMS SUBJECT TO STATE JURISDICTION FOR SAFETY

By Division of Safety of Dams



?. Location of dams in the area in relation to the epicenter of the August 1, 1975 earthquake

PART 2

EVALUATION OF DAMS SUBJECT TO STATE JURISDICTION FOR SAFETY

By Division of Safety of Dams

The responsibility and authority for administration of Part I of Division 3 of the California Water Code, which pertains to supervision for safety of dams and reservoirs, rests with the Department of Water Resources.

Article 3 of Chapter 4 of Part I requires the Department to immediately employ any remedial means necessary to protect life and property if the condition of any dam or reservoir is so dangerous as not to permit time for issuance of and enforcement of an order relative to maintenance and operation, and requires that the Department shall continue in full charge and control of such dam of reservoir until the emergency has passed.

Authority for administration of Division 3 is delegated by the Director to the Division Engineer of the Division of Safety of Dams for all jurisdictional dams, including those owned by the Department of Water Resources and operated by the Division of Operations and Maintenance. To enable prompt recognition of any condition that might require the Division of Safety of Dams to act under Article 3, the Division has established procedures for reacting to seismic events that threaten the safety of dams and reservoirs under its jurisdiction.

Part 2 describes the actions taken by the Division of Safety of Dams during the Oroville earthquake and summarizes the resulting evaluation of the performance of jurisdictional dams in the affected area, including the Department owned dams of the Oroville complex. It also discusses (1) new studies of the seismicity of the area affected by the event; and (2) the effect of the earthquake on seismic criteria that should be used for both design of new structures and evaluation of the adequacy of existing structures in the general area.

Figure 59 shows the location of the dams in the area in relation to the epicenter of the August 1975 earthquake. Most of the dams within a 64-kilometre (40 mile) radius were inspected by Safety of Dams engineers. The owners of all other major dams in the same area inspected their structures and reported no damage. The only damage to jurisdictional dams observed by Safety of Dams engineers consisted of minor cracking in Thermalito Forebay and Afterbay Dams, structures located relatively close to the epicenter. In addition, some existing spalling of a spillway wall joint at Oroville Dam may have been slightly enlarged by the event.

Field Investigation

Following normal procedure, the DWR Earthquake Engineering Section notified the Division of Safety of Dams of the occurrence of an earthquake near Oroville with a magnitude of 4.7 immediately following the event at 0927 (9:27 a.m.) PDT on August 1, 1975. At that time the Division was also notified of a lesser (magnitude 3.6) shock that had occurred 42 minutes earlier.

The appropriate Division Regional Engineer was immediately informed of the event, and the owners of all major dams

considered sufficiently close to the epicenter to be affected by the shock were contacted by telephone.

State Water Project dams -- particularly Thermalito Afterbay Dam -- are located close to the epicenter, and the operating personnel for those dams were telephoned immediately. No obvious damage to project hydraulic structures was reported at that time, although general structural damage of unknown severity to buildings in the Oroville area was reported.

At the time of the notification by the Division of Safety of Dams, surveillance personnel were already reading piezometers and seepage weirs at Oroville Dam and visually inspecting all project dams of the Oroville complex. A short time later the Regional Engineer received a telephoned report that neither significant changes in seepage nor visual signs of distress had been observed.

Oroville Wyandotte Irrigation District, Yuba County Water Agency, Brown's Valley Irrigation District and Thermalito Irrigation District each own one or more major dams in the Oroville area. They were requested to inspect those dams and report back. In most instances the owners had completed the inspection of their dams by noon. All reported no damage.

The main shock of the August 1 Oroville earthquake occurred at 1320 PDT and was first reported to have a magnitude of between 5.9 and 6.2. The owners of all major dams located within a 64-kilometre (40-mile) radius of the epicenter (Figure 59) were telephoned and requested to inspect their dams (most were already doing so). No unusual circumstances were observed except at New Bullards Bar Dam and at Oroville Dam.

New Bullards Bar Dam

New Bullards Bar Dam is a variable-radius thin-arch dam 194 metres (635 feet) high. Operating personnel reported turbidity of the seepage water, with intense discoloration occurring following each aftershock. Personnel kept the dam under close surveillance, reporting frequently to the Safety of Dams field engineer, and the dam was thoroughly inspected by the latter and the owner's engineer on August 2, the day following the main event. The Safety of Dams engineer reported that the foundation seepage water was clear at the beginning of his inspection, but that for a few minutes during the inspection, the water became heavily discolored and then quickly cleared up. It was learned after the inspection that a strong aftershock (not felt at the dam) had occurred at that time.

The only other visual indication of effects from the earthquake was a sudden decrease in the foundation seepage rate, which did not return to normal for several weeks. Subsequent observation and analyses of plumb line deflection and foundation deformation meters a few days after the event indicated normal performance of the dam.

Oroville Dam

Discoloration of water in the powerplant tailrace and in the releases to the Palermo Canal through the left abutment outlet was reported by operating personnel at Oroville Dam. Two engineers from the Division of Safety of Dams travelled to Oroville to inspect the structure.

The Safety of Dams engineers observed that the Oroville O&M Center was on emergency status and maintaining close surveillance of the performance of all structures of the State complex.

The center was prepared to react immediately in the interests of public safety in the event of a structurally damaging shock. (Strong aftershocks occurred every few minutes for several

hours following the main event and, at the time of the inspection, it was not yet clear that the main event had occurred). Liaison had been established with Civil Disaster Officials and the media, and surveillance personnel continued to observe surveillance instruments and conduct visual inspections as the strong aftershocks continued.

The Safety of Dams engineers inspected Oroville Dam embankment, the power plant tailrace, and Palermo Canal. They observed that the tailrace water had cleared up and remained clear during the series of aftershocks. The Palermo Canal was clearing up gradually.

One Safety of Dams engineer remained in Oroville overnight to review all the instrumentation data for the Oroville complex dams. (He would also be on hand in the event of any problems that might require action by the Division of Safety of Dams). Preliminary examination, later verified by more detailed review of the instrumentation data, indicated that the response of Oroville Dam was satisfactory.

Oroville Dam and Lake and other structures of the complex were subjected to particularly close scrutiny by the Division of Safety of Dams because the Oroville facilities are very close to the epicenter, have a high hazard potential, and are relatively new structures. On August 2, the embankment crest, groins and side slopes and the spillway of Oroville Dam were inspected. No signs of distress were observed. Concurrently, operating personnel traversed the foundation gallery, measuring all drains, and reported only a very minor increase in seepage since the last detailed observation just preceding the earthquake.

Maintenance personnel accompanied by a Safety of Dams geologist examined the entire reservoir perimeter from the air in the week following the earthquake to see if any large landslides had been triggered by the event. No gross instabilities of the perimeter were detected.

The piezometers were observed by operating personnel on August 2 following the 1024 (10:24 p.m.) shock (magnitude 4.2), again following the 1359 (1:59 p.m.) shock (magnitude 5.1), and at frequent intervals for some time thereafter. The piezometers continued to indicate that the dam was performing satisfactorily and there was no reoccurrence of turbidity in the tailwater or Palermo Canal. It was concluded that the turbidity observed in the tailwater was due to disturbance of fine sediments in the conduit or near the intake structure, rather than an indication of transporting of foundation or embankment materials.

Review of Oroville Dam Instrumentation

The chief of the Division of Safety of Dams instrumentation unit worked very closely with the Operations and Maintenance surveillance personnel for several days in interpreting and evaluating the instrumentation data, and participated in the meeting with the Special Consulting Board for Oroville Earthquake the week following the earthquake. The following is his report of the preliminary review of the instrumentation data and was included in a memorandum to the Director of Water Resources on August 20, 1975:

"Prompted by the morning earthquakes of August 1, field procedures were undertaken by the operating personnel to record all piezometer pressures in the dam. The first 36 piezometers had been observed and recorded when the main

shock struck at 1320 hours. The reading procedures were then repeated in full. Thus, for piezometers 1 to 36 (below Elevation 500), data were recorded within hours before and after the main shock. The equivalent comparison for piezometers 37 through 57 (above Elevation 500), spans a period of a week from prior reading on July 25. Piezometric comparisons at these levels were therefore functions of both the earthquake and the higher reservoir level of the prior week.

"The pressure rise which accompanied the main shock was most evident on the lower group of piezometers, registering nominal increases of 23 to 27 feet of head (10 to 12 psi) at Elevations 340, 400 and 470. Pressure rises above Elevation 470 were evident only at two piezometers, No. 44 (Elevation 610) and No. 49 (Elevation 680).

"All piezometers were again read twice on August 2, twice on August 3, once on August 4, and subsequently; and the pressures have remained fairly constant.

"Observations of settlement and horizontal displacement were made shortly after the earthquake in the vertical and horizontal movement devices. As reported by the Division of Operations and Maintenance personnel at the meeting of the Consulting Board for Earthquake Analysis on August 8, there was no indication of settlement. Neither was there indication of horizontal movement at the downstream ends of the horizontal devices, although internal deflections of 0.04 to 0.06 foot were detected, with precision of measurement of about 0.02 foot. It will require an additional period of time to acquire survey data from surface monumentation on the dam and in the reservoir area.

"Also, as reported at the August 8 board meeting, there were no significant changes in the deformations measured within the core block area, across the old construction crack, or within the rock mass adjacent to Hyatt Powerplant chamber.

"There are some instruments which, to our knowledge, have not yet been observed subsequent to this earthquake. These include instruments in the spillway, including uplift piezometers, and instruments in the tunnel plugs and river outlet structures.

"Preliminary indications from the voluminous records of strong motion monitoring systems in the dam indicate that there were several losses of records, or partial records, due to malfunction of various components of the equipment. These systems were "pioneered" for Oroville Dam, the first of their kind. The designs and specifica-

tions were later upgraded for similar systems installed in Castaic and Perris Dams. The intent was to utilize the experience and knowledge subsequently gained to upgrade and renovate the Oroville seismic systems at a later date. To a limited extent, this had been done. As recently as 1974, battery supplied "uninterruptible" power for the Oroville systems was installed. Replacement of the acceleration recorders, however, was never accomplished. The recorders, originally acquired from surplus equipment within the Department, were ultimately to be replaced by quick starting recorders with sufficient channels for dual recording of each accelerometer at two levels of amplification.

"Other items of deficiency also exist in these systems, and these should be investigated and appropriate action taken. The seismic records are vital to the process of verifying the full scale, in situ, dynamic properties of the dam."

It is stated in the preceding quote that pressure rises were evident above elevation 470 only at two piezometers. This statement was incorrect. Reexamination of the piezometer data showed nominal pressure rises at nearly all piezometers located in the core.

Surface survey results obtained in August 1975, following the earthquake, were compared with the regular mid-year survey of July 1975 just prior to the earthquake. The August 1 quake caused only slight changes in the data. The greatest amount of settlement observed at the embankment crest was about 10 millimetres (0.03 foot). This is the settlement that would normally have occurred during continuing consolidation over a six-month period in the absence of any earthquake. Changes in the horizontal surface surveys were also slight. Several of the crest monuments revealed upstream displacements, while those on the downstream slope displaced downstream. The displacement reached a maximum of 15 millimetres (0.05 foot) upstream and 12 millimetres (0.04 foot) downstream.

Settlements in the Oroville area portrayed in Part 1 of this bulletin under "Geodetic Work" indicate that subsidence of 5 to 10 millimetres (0.016 to 0.03 foot) occurred at Oroville Dam and Bidwell Canyon Dam during the six months following the earthquake.

Data subsequently acquired from instrumentation in the spillway, tunnel plug, and river outlet structure that had not been observed at the time of the August 20, 1975 report did not disclose any unusual conditions.

Changes in operating procedures have been made to minimize losses of acceleration records, such as those lost during the earthquake due to a temporary power failure. Better maintenance of electronics has improved the quality of the accelerogram traces. However, the old surplus recorders are still being used (February 1977) to record accelerations at a single level of amplification, and investigations to determine how the system should be renovated are continuing.

Further deterioration of the dynamic stress monitoring system beyond that revealed by the system's performance during the earthquake resulted from a lightning strike in September 1976.

The system may not be repairable because the damage appears to be in instrument components that are deeply embedded in the embankment, although it still can be used for periodic determinations of static stress at some locations.

The strong-motion accelerographs in the crest vault and in the grout gallery were replaced with new accelerographs in late 1975. A further expansion of this system is presently under construction (February 1977) to include five instruments interconnected for common triggering and timing.

A summary of detailed analysis of the instrumentation data acquired at Oroville Dam during and since the earthquake, is presented in Part 1, of this bulletin. The Division of Safety of Dams has reviewed the material and concurs in the conclusions.

Thermalito Forebay Dam

On August 6, Thermalito Forebay Dam was inspected and some very minor cracking previously noted by the operating personnel was examined. What caused the cracking, other than the shaking of the earthquake, is not known, but in any event the cracks were judged not to have serious effect on the safety of the dam in any way.

Thermalito Afterbay Dam

Several minor longitudinal cracks were observed in the embankment, generally along the upstream crown on both sides of the river outlet structure. A transverse crack was observed in the embankment at its contact with the concrete gate structure at the outlet. Sloughing of the riprap occurred in the channel from Thermalito Forebay Dam into Thermalito Afterbay Dam, but it has no relation to the safety of either structure.

Other Dams in Area

In addition to Oroville and New Bullards Bar Dams, three other dams, Lake Wyandotte, an older earth dam; Virginia Ranch, a modern earth dam; and Los Verjels, an old multiple arch dam; were inspected by Safety of Dams personnel on August 2. No damage was observed.

In the week following the earthquake, 36 of the 48 jurisdictional dams located within 64 kilometres (40 miles) were inspected by Safety of Dams personnel. Those dams not inspected either are small structures or are located near the 64-kilometre limit. The larger dams were inspected by the owners who reported no damage.

On the basis of the field inspections, supplemented with interviews of owner's representatives and review of instrumentation data were available, it was concluded that the jurisdictional dams located in the study area performed adequately during the earthquake and that all were in safe condition. As a matter of prudence, closer-than-normal surveillance was practiced for several months to be certain that no adverse changes were occurring subsequent to the post-earthquake inspection. As of this writing (February 1977) no such changes have been found.

Discussion of Geology and Seismicity of Affected Area as it Relates to Performance of Dams

Before the 1975 Oroville earthquake, seismological considerations applied to dam design in the northern foothills of the Sierra Nevada had centered on a rather obscure earthquake that occurred February 8, 1940. This moderate earthquake (called the "ghost" earthquake by some in allusion to its seemingly isolated occurrence) was the largest ever recorded in this region, where few quakes had occurred previously.

It was reported to have a magnitude of 6.0, but because its point of origin was located in the remote foothill country north of Oroville, no significant damage occurred. No fault break or other surface manifestations of movement to identify any originating geologic structure was ever reported.

Although the 1940 earthquake was recognized as the significant event for purposes of design, the level of seismic activity it represented had little effect on design criteria for dams in the Oroville area. New techniques for modeling the dynamic responses of dams are changing that. With the advent of these techniques in the early 1970s, the 1940 earthquake took on new importance, and a closer scrutiny was made of the basic records.

Reevaluation of the original seismograms of the 1940 event yielded a significantly different location for its epicenter, 40 kilometres (25 miles) northwest of the original site, and lowered the estimate of its magnitude from 6.0 to 5.7. Soon after learning of the revised epicenter location in 1973, the Division of Safety of Dams noted its proximity to a linear topographic feature which had been mapped as a fault during a county reconnaissance in 1966. The prospect of finding a surface expression of the originating tectonic structure for that earthquake suddenly looked better, but subsequent geologic examinations of the linear feature refuted its identification as a fault.

Little regional work has been done since the early 1900s to learn the geological and seismological character of the northern Sierra foothills; and even though those turn-of-the-century studies were outstanding accomplishments and remain the principal reference works on the area, they paid little heed to many of the features that are of concern today. It took the emerging development of dynamic response techniques and national concerns for the environment to get modern geological, geophysical, and seismological studies started. Pacific Gas and Electric Company, in a search for acceptable sites for nuclear power plants in the eastern San Joaquin and Sacramento Valleys beginning in 1973, was the first organization to initiate extensive studies of potential fault activity in the Sierra foothills. Those studies continue today (February 1977).

The Oroville earthquake intensified the demand for geologic studies. The damage to buildings, the continuing aftershocks, the local presence of the very large Oroville Dam and associated facilities, and the discovery of tectonic ground cracks that could logically be associated with elements of the supposedly dormant Foothills Fault Zone, all stimulated a demand for an immediate appraisal of the earthquake potential of the Sierra foothills. Perhaps an even more influential factor generating demand for more studies, however, was the recognition that the Oroville earthquake tended to indicate that the 1940 earthquake was not just an isolated event after all. Here, in just a short span of 35 years, were two moderate earthquakes in the same general area: clearly a circumstance that could not be ignored.

Dam designers need the answers to two basic questions when considering the seismic stability of a structure. First, where are the potentially active faults in relation to the dam? And second, what is the magnitude of the earthquake that can be expected to be generated by the faulting? Answers to the latter question involve an assessment of the extent and continuity of the potentially active faults. Concerning dams in the Oroville area, the question resolves mostly into determining if the Cleveland Hill Fault, the feature along which the ground ruptures occurred during the Oroville earthquake, is indeed part of a larger fault system. Its proximity to the Foothills Fault system, that

large, braided fault complex that extends 300 kilometres (190 miles) from Mariposa on the south to Oroville and Belden on the north, naturally raises the question of its relationship to that system.

As designers and constructors of large dam projects in the Sierra foothills, state and federal agencies are now deeply involved in regional studies aimed at producing answers to those and other questions. The Department of Water Resources, as owner of the Oroville Dam and associated facilities, clearly has need for the best available assessment of earthquake potential and has studies underway in the Oroville area. The U. S. Army Corps of Engineers has begun new studies of its Parks Bar and New Melones projects. The U. S. Bureau of Reclamation is working on seismic reevaluation studies of the Auburn project.

The U. S. Bureau of Reclamation is working on seismic reevaluation studies of the Auburn project.

There also are many existing dams and reservoirs in the foothills area. More than 200 dams, some of which are among the largest in California, within the area of influence of the Foothills Fault system, are subject to State jurisdiction for safety. The Division of Safety of Dams initiated a comprehensive study of the entire fault system in January 1977.

Interesting and relevant facts are beginning to emerge from the geologic studies. Whereas, up to several years ago, activity on the Foothills Fault system was thought to have died out more than 100 million years ago, recent evidence indicates that at least local faults were active in many separate areas -- widely distributed along the fault system -- since that time.

How recently some of the activity may have occurred, and how continuous the fault zones are, still must be determined. The Sierra foothills comprise a particularly difficult area in which to get those answers. To determine recency, for instance, requires deposits or other geologic features whose age can be determined to be close to that of the latest faulting, and whose structural relationships to the latest faulting can be known with certainty. Unfortunately, the Sierra Foothills are frequently lacking in such deposits and features. Another aspect of the problem appears to be that the frequency of fault movement is low enough that erosion removes much of the surface evidence before the next seismic event occurs, thus eliminating the compounding effect that usually makes such evidence readily detectable.

Tracing features in the belt of metamorphic rocks that comprise the bedrock surrounding most of the Foothills Fault system is also exceedingly difficult. Most of the bedrock has been extensively deformed, broken, sheared, partially healed, and partially reconstituted. Its regional fabric parallels the fault system, and singling out those topographic and geologic features which pertain strictly to the fault system requires detailed and painstaking study.

The Oroville earthquake emphasized the need for a determination of the seismic potential of the Sierra Foothill region. The intensive studies of fault activity now in progress should soon enable geoscientists to systematically assess the potential for damaging earthquakes in the area. The studies will provide input to dynamic response analyses of the many major dams in the Sierra foothills.

Evaluation of Seismic Stability of Dams in Affected Area

Following the Oroville earthquake the Division of Safety of Dams (1) examined the seismic design criteria used in design of the 48 jurisdictional dams

located within a distance of 64 kilometres (40 miles) of the epicenter; (2) evaluated the seismic criteria and design earthquake that now should be used in the area in light of the event; and (3) considered the possible need to reanalyze the dams in question.

Seismic Criteria Used in Design of Dams in Affected Area

Only within the last several years have dynamic response techniques been developed to approximate and evaluate the time-history of stresses occurring in an earthfill or concrete dam during earthquake shaking. All of the dams in the area predate development of such techniques. Therefore, if any seismic design criteria were utilized in their design, they followed a pseudostatic approach, whereby the effects of earthquake motions anticipated in the area were represented by a constant load. The assigned lateral load was generally 10 percent of the structure weight.

It has been the Division's experience that pseudostatic techniques using the 10-percent lateral force usually do not change the configuration of earth dams as dictated by normal static criteria; this is because design safety factors are reduced in considering earthquake loads. A 15-percent lateral force, which is often used in the more earthquake-prone areas of the State, generally results in modest changes in earthdam sections to satisfy design safety factors.

Neither a specific design earthquake nor time-history of motion was used in original design of any of the dams in the zone of influence. Such specific earthquake representations are useful only for the recently developed dynamic response analyses.

Appropriate Seismic Design Criteria for Current Use in Affected Area

The selection of the potential seismic criteria and design earthquakes which, in light of the Oroville earthquake, should now be used involves two questions. First, what earthquake in the immediate Palermo-Oroville area is considered the maximum credible event? Second, over what area in the Sierra foothills does this earthquake apply? If the studies conducted to answer the second question indicate that an active fault zone of significant length exists, then an even greater maximum credible earthquake than now considered appropriate may have to be considered.

For the present, we agree with the Department's Special Consulting Board for the Oroville Earthquake, which recommended that a magnitude 6.5 earthquake in the immediate Oroville area be considered in evaluating project facilities. In addition, until current geological studies provide a more definitive assessment of earthquake potential, the Division regards a magnitude 6.5 earthquake the appropriate level of maximum credible event to consider in evaluating dams along the entire Foothills Fault system. Maximum bedrock accelerations relatively close to the epicenter of such an earthquake, based on empirical tabulations presented in recent literature, would be approximately 0.5g. It is interesting to note that most accelerations recorded during the Oroville earthquake and aftershocks were significantly less than would be estimated by these tabulations.

Need for Reanalysis of Seismic Stability of Dams in Affected Area

The need for reanalysis of the seismic stability of dams in the affected area depends in each case on the age, type and condition of the structure, the distance from an assumed epicenter and the damage potential. Figure 60 presents an estimate of the diminishing effects of a magnitude 6.5 earthquake with distance from the epicenter. Historical performance of dams indicates that they can withstand accelerations up to 0.2 - 0.3g for the relatively short earthquakes.

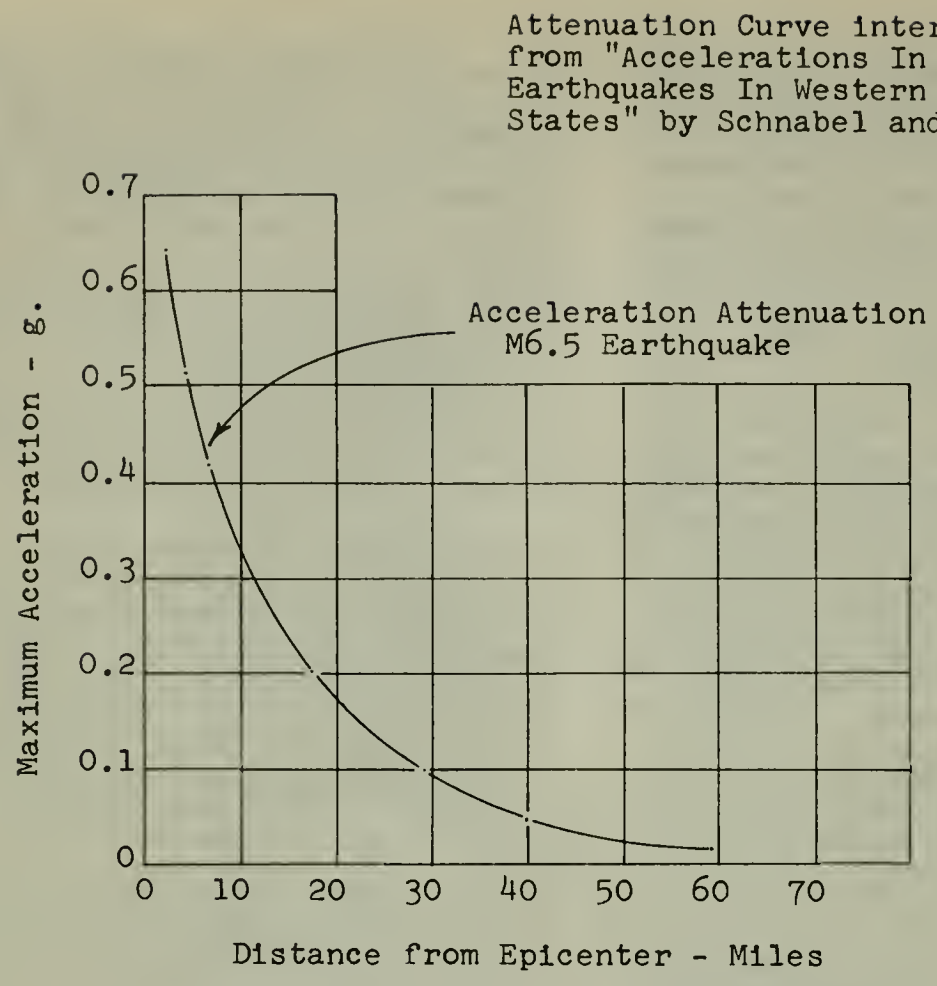


Figure 60. Estimate of diminishing effects of a magnitude 6.5 earthquake

This means that any dam located about 24 kilometres (15 miles) or more from a magnitude 6.5 epicenter would not be expected to experience serious damage.

A limited amount of experience from actual earthquakes and from dynamic analysis reports recently reviewed indicates that embankments constructed under modern methods and controls will not be seriously damaged, even when located adjacent to a magnitude 6.5 earthquake.

The first phase of the statewide seismic reevaluation program initiated after the 1971 San Fernando earthquake involved hydraulic fill dams. Two hydraulic fill dams are located within 64 kilometres (40 miles) of the epicenter, and already had been analyzed as part of the seismic reanalysis program prior to August 1, 1975. A magnitude 6.5 earthquake near Oroville would produce maximum accelerations somewhat greater than those studied in the reanalysis report for one of the dams. Although the increase in maximum credible acceleration is not expected to be critical, the Division intends to review that reanalysis report considering the increased level of shaking.

The second phase of the program involves suspect embankment dams other than hydraulic fills. Analyses of these dams are being requested on a priority system which considers seis-

mic activity, damage potential, and condition of the dam. Older dams in the Oroville area did not rank high in need for reevaluation under the previous estimates of seismic activity of the area. Using a magnitude 6.5 earthquake in the Oroville area does not significantly change the priority for reevaluation of these older dams.

Dynamic Analysis of Earth Dams of Oroville Complex

Dynamic response analyses of Oroville, Thermalito Forebay and Thermalito Afterbay Dams currently are in progress. As described in Part I, this work is scheduled for completion in 1977.

Summary

During the week following the Oroville earthquake, all but a few of the major dams within 64 kilometres (40 miles) of the epicenter were inspected by Safety of Dams engineers. Other dams, which were near the outer limits of the area, were inspected by the owners. The effects observed consisted of temporary changes in seepage flows and piezometer pressures; temporary turbidity in tailwater at Oroville and New Bullards Bar Dams; and minor embankment cracking at Thermalito Forebay and Afterbay Dams.

On the basis of the field inspections and preliminary review of instrumentation data, which revealed no indication of structural distress, it was concluded that the performance of all dams was satisfactory during the event. Nothing has been indicated by the performance of the dams since the earthquake to change that conclusion.

The owners of dams with high damage potential reacted responsibly to the earthquake, were prompt in the inspection of their dams, and continued to monitor the structures closely for some time after the event.

Some significant questions were raised by the occurrence of the Oroville earthquake concerning seismicity of the area. They will remain unanswered, however, until the current seismic and geologic studies are concluded. These questions involve the length and continuity of the Foothills Fault system, and the possibility that geologic conditions could support a maximum credible earthquake in excess of magnitude 6.5 along that fault. The Division of Safety of Dams is acutely interested in certain phases of that program, which also involves several federal and state agencies concerned with dams, seismicity, and geology. The Division of Design and Construction is conducting a detailed geologic investigation in the immediate vicinity of the Oroville complex of the State Water Project to locate any possible faulting that could affect the integrity of the dams and other structures of the complex. Federal agencies are reevaluating the seismic design criteria for dams under construction or proposed in the Sierra foothills area.

Fifteen dams are located in or near the Palermo-Oroville area, where a maximum credible earthquake up to magnitude 6.5 now is considered appropriate. Nine of these dams were constructed since 1950, using modern construction practices, and can be expected to exhibit excellent performance if subjected to magnitude 6.5 earthquake. Conditions at the six older dams in the immediate area are not as well known; they are being considered for seismic reanalysis on a priority basis along with all other jurisdictional dams in the State. All six dams are relatively low with small impounding capacities.

Dynamic response analyses were recently completed on the two hydraulic fill dams located within the influence of the 1975 Oroville earthquake. The report on one of these dams will be reconsidered for the slightly higher level of shaking that would be anticipated from a magnitude 6.5 event on the nearest capable active fault.

Dynamic response analysis of the major earth dams of the Oroville complex is under way and is scheduled for completion in 1977.

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APPENDIXES

Appendix A

Historical Seismicity Near Oroville, 1851-1975

Explanation of Table

Date and Time: Origin time of earthquake in Greenwich Mean Time

LAT and LONG: Epicenter of earthquake.

Quality: Quality of epicenter determination, A excellent, B good, C fair, D poor.

Mag: Richter magnitude (M_L)

Stations Recording: Number of stations recording the earthquake

Felt: F indicates if the earthquake was felt.

Comments: Intensity values are Rossi-Forel Scale before 1932.

Appendix A - Historical Seismicity Near Oroville, 1851-1975

FROM RECORDS OF UC BERKELEY SEISMOGRAPHIC STATIONS

MO	DA	YR	HR	MIN	SEC	LAT	LONG	DUP	MAG	RSE SG	FOC	MAXIMUM INTENSITY, COMMENTS
12/	2/1851		-0-	-0-	-0.	39.58	120.83	D			F	DOWNIEVILLE.
12/31/1851			-0-	-0-	-0.	39.58	120.93	D			F	V DOWNIEVILLE.
1/25/1855			6-	-0-	-0.	39.58	120.83	D			F	VII DOWNIEVILLE.
7/13/1855			-0-	-0-	-0.	39.58	120.83	D			F	III GIBSONVILLE.
8/ 8/1857			19-	-0-	-0.	39.58	120.83	D			F	V RABBIT CREEK.
2/10/1858			-0-	-0-	-0.	39.58	120.83	D			F	V KANAKA FLAT.
9/16/1861			10-	-0-	-0.	39.25	121.00	D			F	SIERRA VALLEY.
7/ 3/1862			1-	-0-	-0.	39.67	121.00	D			F	VI LA PORTE.
10/18/1863			-0-	-0-	-0.	39.17	121.67	D			F	YUBA CITY.
8/18/1864			6-	39-	-0.	39.25	121.00	D			F	IV NEVADA CITY.
8/18/1864			13-	18-	-0.	39.25	121.00	D			F	VI GRASS VALLEY, NEVADA CITY, MARYSVILLE, YUBA CITY.
7/14/1866			6-	30-	-0.	39.67	121.00	D			F	V LA PORTE, ROWLAND FLAT, ST LOUIE, PORT WINE, SACRAMENTO, SAN FRANCISCO, AND STOCKTON.
9/ 5/1866			13-	-0-	-0.	39.67	121.00	D			F	LA PORTE, ROWLAND FLAT, ST. LOUIS, AND PORT WINE.
12/ 2/1867			7-	12-	-0.	39.25	121.00	D			F	VII NEVADA CITY AND FOREST CITY.
6/ 2/1868			9-	30-	-0.	39.58	120.83	D			F	VII DOWNIEVILLE AND FOREST CITY.
9/17/1869			-0-	-0-	-0.	39.25	121.00	D			F	NEVADA CITY. 2 SHOCKS.
12/26/1868			-0-	-0-	-0.	39.25	121.00	D			F	NEVADA CITY.
12/21/1869			4-	-0-	-0.	39.17	121.08	D			F	V GRASS VALLEY.
12/27/1869			1-	30-	-0.	39.17	121.58	D			F	VIII MARYSVILLE
12/27/1869			5-	-0-	-0.	39.17	121.58	D			F	MARYSVILLE.
12/27/1869			10-	-0-	-0.	39.17	121.58	D			F	IX MARYSVILLE, SACRAMENTO, OROVILLE, ETC. EPICENTER PROBABLY NEAR VIRGINIA CITY,NEVADA.
12/27/1869			10-	10-	-0.	39.17	121.58	D			F	MARYSVILLE.
3/ 4/1870			-0-	-0-	-0.	39.17	121.08	D			F	GRASS VALLEY.
5/ 4/1870			-0-	-0-	-0.	39.17	121.08	D			F	GRASS VALLEY.
3/28/1872			-0-	-0-	-0.	39.25	121.00	D			F	NEVADA CITY.
4/28/1872			-0-	-0-	-0.	39.25	121.00	D			F	V NEVADA CITY.
4/30/1872			-0-	-0-	-0.	39.17	121.58	D			F	III MARYSVILLE. 2 LIGHT SHOCKS.
1/24/1875			12-	-0-	-0.	39.50	121.58	D			F	VI BUTTE, PLUMAS, AND SIERRA COUNTIES. OROVILLE, TAYLORSVILLE, GREENVILLE, DOWNIEVILLE, AND CARSON CITY, NEVADA.
12/ 2/1875			22-	40-	-0.	39.17	121.58	D			F	MARYSVILLE. 3 SHOCKS.
12/ 3/1875			-0-	-0-	-0.	39.17	121.08	D			F	V GRASS VALLEY. CARSON CITY, NEVADA.
12/25/1875			-0-	-0-	-0.	39.17	121.08	D			F	GRASS VALLEY. EVENING.
5/27/1879			4-	40-	-0.	39.42	122.00	D			F	PRINCETON.
7/17/1885			5-	15-	-0.	39.75	121.83	D			F	IV CHICO AND PRINCETON.
4/24/1888			4-	48-	-0.	39.25	121.00	D			F	VIII NEVADA CITY. PRECEDED BY RUMBLING SOUNDS. GRASS VALLEY - FELT IN THE IDAHO MINE BELOW THE 1600 FEET LEVEL. MARYSVILLE, DOWNIEVILLE, TRUCKEE, COLFAX, SACRAMENTO, DUTCH FLAT, DIXON, BIGGS, SANTA ROSA, OROVILLE, SAN FRANCISCO.
4/10/1888			11-	40-	-0.	39.58	120.83	D			F	IV DOWNIEVILLE, GRASS VALLEY.
2/15/1891			10-	30-	-0.	39.58	120.83	D			F	DOWNIEVILLE.
3/ 3/1893			14-	15-	-0.	39.17	121.08	D			F	GRASS VALLEY.
3/ 3/1893			14-	40-	-0.	39.25	121.00	D			F	NEVADA CITY, IOWA HILL.
12/12/1899			-0-	-0-	-0.	39.75	121.83	D			F	CHICO.
12/13/1899			-0-	-0-	-0.	39.75	121.83	D			F	CHICO.
12/19/1899			-0-	-0-	-0.	39.75	121.83	D			F	CHICO.
12/20/1899			-0-	-0-	-0.	39.75	121.83	D			F	CHICO.
11/14/1901			3-	-0-	-0.	39.75	121.83	D			F	III CHICO.
1/16/1902			-0-	-0-	-0.	39.33	121.08	D			F	NORTH SAN JUAN.
7/24/1903			20-	26-	-0.	39.50	122.17	D			F	VII WILLOWS. EARTHQUAKE BEGAN WITH A RUMBLING NOISE AND WAS SUCCEEDED BY A TWISTER. ATMOSPHERIC CONDITIONS PRIOR TO THE SHOCK WERE PECULIAR. ALSO AT MAGALIA, CHICO, COLUSA, GRASS VALLEY, GREENVILLE, LA PORTE, MARYSVILLE, MEADOW VALLEY, NEVADA CITY, ORLAND, OROVILLE, PALERMO, SACRAMENTO, TEHAMA, AND WHEATLAND.
10/29/1904			-0-	-0-	-0.	39.50	121.50	D			F	BRUSH CREEK.
5/15/1905			-0-	-0-	-0.	39.25	121.00	D			F	NEVADA CITY, OAKDALE, AND YOSEMITE.
5/15/1906			7-	32-	-0.	39.17	121.08	D			F	VI GRASS VALLEY. 3 DISTINCT SHOCKS.
9/ 9/1906			13-	15-	-0.	39.17	121.08	D			F	GRASS VALLEY, NEVADA CITY, AND PILOT CREEK. FELT IN NEVADA.
2/ 5/1907			13-	25-	-0.	39.67	121.00	D			F	LA PORTE.
5/ 2/1908			-0-	-0-	-0.	39.67	121.00	D			F	LA PORTE.
1/ 7/1909			12-	40-	-0.	39.50	122.17	D			F	WILLOWS.
1/ 3/1910			13-	-0-	-0.	39.25	121.00	D			F	V NORTH CENTRAL SIERRA. NEVADA CITY, DOWNIEVILLE, IOWA HILL, MAGALIA, NORTH BLOOMFIELD, PILOT CREEK, REPRESA, SACRAMENTO, SONORA, AND BECKWITH.
8/ 9/1909			9-	-0-	-0.	39.58	120.83	D			F	DOWNIEVILLE AND LA PORTE.
8/ 9/1909			14-	-0-	-0.	39.58	120.83	D			F	DOWNIEVILLE AND LA PORTE.
5/23/1909			4-	40-	-0.	39.67	121.00	D			F	LA PORTE.
6/23/1909			7-	24-	-0.	39.33	120.92	D			F	VIII SIERRA COUNTY. AT DOWNIEVILLE CHIMNEYS DAMAGED, AFTERSHOCKS CONTINUED FOR TEN DAYS. ALSO HEAVY AT NORTH BLOOMFIELD, DOWNIEVILLE, AND BOWMANS DAM. VI-VII AT NEVADA CITY, GRASS VALLEY, TRUCKEE, EMIGRANT GAP, LA PORTE, AND QUINCY. HEAVY AT RENO, NEVADA, MARYSVILLE, OROVILLE, AND SACRAMENTO. IV AT CHICO AND SUSANVILLE. III AT RED BLUFF, REDDING, AND PLACERVILLE. WILLOWS, COLUSA, TEHAMA, AND DUNSMUIR AND SPARKS, NEVADA ALSO REPORTED. THE AREA WITHIN WHICH THE INTENSITY WAS II OR HIGHER PROBABLY APPROACHED 50,000 SQUARE MILES.
6/23/1909			7-	41-	-0.	39.33	120.92	D			F	AFTERSHOCK OF 7-24-0.
6/23/1909			7-	53-	-0.	39.33	120.92	D			F	AFTERSHOCK OF 7-24-0.
6/23/1909			13-	-0-	-0.	39.33	120.92	D			F	AFTERSHOCK OF 7-24-0.
6/23/1909			13-	30-	-0.	39.33	120.92	D			F	AFTERSHOCK OF 7-24-0.
7/ 3/1909			15-	-0-	-0.	39.58	120.83	D			F	DOWNIEVILLE.
7/ 3/1909			22-	-0-	-0.	39.58	120.83	D			F	DOWNIEVILLE. LAST AFTERSHOCK OF 6/23/09, 7-24-0.
7/13/1909			23-	5-	-0.	39.58	120.92	D			F	DOWNIEVILLE AND NEVADA CITY.
11/23/1909			7-	15-	-0.	39.50	122.17	D			F	WILLOWS.
5/19/1910			5-	-0-	-0.	39.33	121.17	D			F	ROBBINS. PERHAPS SAME SHOCK AS FOLLOWING.
4/ 5/1910			1-	31-	16.	39.25	121.00	D			F	NEVADA CITY.

9/ 4/1910	3-30--0.	39.67	121.00	D			F	LA PORTE. RATTLED WINDOWS.
1/15/1912	18-30--0.	39.25	121.00	D			F	NEVADA CITY, STERLING CITY, AND WEST BRANCH.
3/ 3/1913	9-40--0.	39.67	121.00	D			F	LA PORTE.
9/27/1913	5--0--0.	39.67	121.00	D			F	LA PORTE.
9/27/1913	9--0--0.	39.67	121.00	D			F	LA PORTE.
2/18/1914	18-15--0.	39.58	120.83	D			F	VI-VII AT TRUCKEE MEADOWS, RENO, AND VIRGINIA CITY, NEVADA. STRONG AT VERDI, SPARKS, AND CARSON CITY, NEVADA. FELT AT DOWNIEVILLE. RECORDED AT BERKELEY.
10/ 3/1915	1-49--0.	39.42	121.08	D			F	CAMPTONVILLE, AND PLEASANT VALLEY, NEVADA.
3/12/1918	10-30--0.	39.58	120.83	D			F	VIII DOWNIEVILLE. CHIMNEYS THROWN DOWN.
3/12/1918	12-30--0.	39.58	120.83	D			F	DOWNIEVILLE.
12/29/1920	9-59--0.	39.50	122.17	D			F	V WILLOWS. 2 SHOCKS. FELT ALSO AT GLENN AND AT ORLAND.
1/13/1921	10-30--0.	39.50	122.17	D			F	V WILLOWS. ALSO FELT 10 MILES E OF WILLOWS.
4/15/1923	7-15--0.	39.25	121.00	D			F	NEVADA CITY.
12/ 4/1923	20-50--0.	39.42	121.08	D			F	IV CAMPTONVILLE, DURATION 60 SECONDS. AT QUINCY AT 21-05, DURATION 10 SECONDS.
12/29/1927	0-12--0.	39.17	121.08	D			F	III GRASS VALLEY.
1/19/1930	5-43--0.	39.92	121.33	D			F	IV STORRIE.
2/17/1931	13-30--0.	39.75	121.83	D			F	CHICO.
6/16/1932	11-10--0.	39.67	121.00	D			F	IV NEAR TAYLORSVILLE.
4/14/1939	13-15--0.	39.15	121.10	D			F	GRASS VALLEY. BSSA, OCTOBER 1939.
11/ 8/1939	3-25--0.	39.15	121.10	D			F	GRASS VALLEY AND AREA. FELT BY MINERS DOWN TO 4,500 FEET VERTICAL DEPTH.
11/19/1939	12-37--0.	40.00	121.50	D			F	INSKIP BUTTE LOOKOUT (FOREST SERVICE).
2/ 9/1940	8- 5-59.	40.00	121.60		6.6		F	FELT OVER AN AREA OF 28,000 SQUARE MILES OF NORTH-CENTRAL CALIFORNIA. VI AT ALMANOR, BANGOR, BUTTE CITY, CHICO, GRIDLEY, LA PORTE, NEVADA CITY, PARADISE, TEHAMA, AND VINTON. V AT BAXTER, BECKWOARTH, BIGBEN, BLAIRSDEN, CARIBOU, CHESTER, CORNING, CRESCENT MILLS, DE SABLA, DUTCH FLAT, FEATHER RIVER, CAJON, FOREST RANCH, GRANITEVILLE, GREENVILLE, GRIMES, MEADOW VALLEY, MILFORD, MILLVILLE, MINERAL, OROVILLE, PORTOLA, QUINCY, SENECA, SHERIDON, STORRIE, STIRLING CITY, WEIMAR, WESTWOOD, WHEATLAND, WILLIAMS, WOODLAND, AND YOLO.
10/25/1941	7- 8--0.	39.50	122.17	C			F	LAS PLUMAS AND WILLOWS.
11/18/1942	20-20--0.	39.90	121.50	D			F	VI STIRLING CITY. ALSO FELT CHICO, FEATHER RIVER CANYON, LAS PLUMAS, AND STORRIE.
11/18/1942	22-35--0.	39.90	121.50	D			F	SAME FELT REPORTS AS 20-20-0.
5/ 1/1943	5- 0--0.	39.15	121.10	D			F	GRASS VALLEY. (BSSA, JULY 1943).
11/14/1943	22- 3--0.	39.50	122.15	D			F	FELT AT WILLOWS.
9/ 9/1944	10-15--0.	39.35	121.70	D			F	GRIDLEY.
4/20/1945	5-36-10.	39.75	121.65	D			F	VI AT PARADISE. IV AT LAS PLUMAS, STORRIE, AND NE BUTTE CO.
11/ 7/1947	6-50--0.	39.75	121.65	D			F	PARADISE.
11/14/1948	10-30--0.	39.75	121.85	D			F	CHICO.
3/ 3/1949	3-23--0.	39.25	121.50	D			F	LIGHT SHOCKS IN STRAWBERRY VALLEY (YUBA CO.) REPORTED FELT AT 0323, 0502, AND 1030, AND ON 3/4/49 AT 1210.
5/ 5/1949	13-50-51.	38.87	121.03	B	3.6			NEAR AUBURN.
11/ 1/1949	21- 7-34.	39.93	121.72	C	2.0			NORTH OF CHICO.
3/12/1950	4-22-52.	39.17	121.10	C	3.3			SOUTH OF GRASS VALLEY.
7/22/1950	6-37--0.	39.75	121.85	D			F	IV CHICO. FELT AT WILLOWS.
1/27/1958	15-22- 2.	39.50	122.05	C	2.9			SOUTHWEST OF CHICO.
1/ 4/1959	17- 0-29.	39.85	121.95	C	2.4			NORTHWEST OF CHICO.
3/11/1959	2-49-49.	39.77	122.10	C	3.5			NORTHWEST OF CHICO.
4/23/1960	2-21-19.	39.80	121.90	D	3.6			NORTH OF CHICO.
7/24/1960	14-12- 3.	39.87	121.87	B	2.4			NORTH OF CHICO.
10/ 5/1960	1-18- 6.	39.18	121.15	B	3.3			EAST OF MARYSVILLE.
10/15/1961	23-47-12.	39.43	121.42	C	2.7			SOUTHEAST OF CHICO.
12/ 6/1962	12-36-39.3	39.70	121.15	B	2.9	10		NORTHWEST OF OROVILLE.
4/24/1964	7-44- 2.6	39.85	121.27		3.4	15	F	FELT OVER 900 SQ. MI. V AT DOYLE.
4/29/1965	19-25-17.	39.50	122.10		3.6	13		SE OF ORLAND.
4/29/1965	21-28-50.	39.50	122.10		3.2	5		AFTERSHOCK OF 19-25-17.
11/ 8/1965	3-28-50.1	39.96	121.26		3.4	6	F	NW OF QUINCY. FELT BELDEN, STORRIE.
5/24/1966	3-49-35.1	39.78	121.77		4.6	9	F	NE OF CHICO. VI FOREST RANCH, LAS PLUMAS, MAGALIA, PARADISE, YANKEE HILL. V ALTA, BELDEN, BERRY CREEK, BROWNS VALLEY, BUSH CREEK, BUTTE CITY, CAMPTONVILLE, CHALLENGE, CHICAGO PARK, CHICO, CLIPPER MILLS, DOBBINS, FEATHER FALLS, FORBESTOWN, GRASS VALLEY, GRIMES, OREGON HOUSE, OROVILLE, PALERMO, PULGA, RACKERBY, STORRIE, TAYLORSVILLE, WHEATLAND, YUBA CITY.
7/25/1966	13- 5-39.9	39.63	122.12		3.0	6		SW OF CHICO.
2/ 3/1967	15-35- 8.1	39.53	122.15		3.4	7		SW OF CHICO
4/29/1968	0-21-38.6	39.58	122.02		4.7	9	F	SW OF CHICO. FELT OVER APPROXIMATELY 10,500 SQUARE MILES. MAX. INTENSITY VI AT CHICO, BUTTE CITY, WILLOWS. MINOR DAMAGE.
7/22/1968	1- 5- 2.5	39.83	121.45		3.1	10	F	NW OF CHICO. FELT OVER APPROX. 900 SQ. MILES. MAX INTENSITY V AT ARBUIS, CHICO, HAMILTON CITY.
7/22/1968	1- 7-12.	39.93	121.98		3.3	8		NW OF CHICO.
7/ 1/1970	7-55-26.	39.48	122.27		3.6	7	F	15 KM SOUTHEAST OF WILLOWS. REPORTED FELT IN WILLOWS AREA. PLASTER AND DISHES BROKEN.
7/ 1/1970	14-56-50.4	39.49	122.09		3.5	9	F	20 KM SOUTHEAST OF WILLOWS. INTENSITY IV AT ARBUIS, GLENN, DURHAM, ELK CREEK, ORLAND, PRINCETON, RICHVALE, AND WILLOWS.
7/ 6/1970	11-52-39.2	39.38	122.03		3.0	6		20 KM SOUTHEAST OF WILLOWS.
3/26/1971	4- 9-17.3	40.00	121.35		3.2	4		SW OF LAKE ALMANOR
8/ 6/1971	23-29-44.3	39.51	122.11		3.8	9	F	SW OF CHICO. FELT IN AREAS OF BUTTE, COLUSA, GLENN, AND SUTTER COUNTIES. INTENSITY IV AT BERRY CREEK, CHICO, COLUSA, GLENN, GRIDLEY, AND WILLOWS. INTENSITY I-III AT BIGGS, DURHAM, FOREST RANCH, MAXWELL, MERIDIAN AND PRINCETON

APPENDIX B

MODIFIED MERCALLI EARTHQUAKE INTENSITY SCALE OF 1931 (ABRIDGED)

I	Not felt except by a very few under especially favorable circumstances. (I Rossi-Forel Scale.)
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II Rossi-Forel Scale.)
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale.)
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. (IV to V Rossi-Forel Scale.)
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale.)
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale.)
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars. (VIII Rossi-Forel Scale.)
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Change in well water. Disturbed persons driving motor cars. (VIII+ to IX Rossi-Forel Scale.)
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel Scale.)
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale.)
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

TABLES

Table I

Hypocentral Parameters of Oroville Earthquakes
June 28, 1975 - March 31, 1976

Explanation of Table

Origin: Time of Earthquake in Greenwich Mean Time (GMT). To get local time subtract eight hours for Pacific Standard Time (PST) and seven hours for Pacific Daylight Time (PDT).

LAT N, LONG W: Latitude North, Longitude West. Geographic coordinates of earthquake.

Depth: In kilometres.

Mag.: Richter magnitude (M_L)

RMS: Root-mean-square of time differences between observed and computed time of first arriving wave at stations used in hypocenter computation.

ERH, ERZ: Horizontal (H) and vertical (Z) standard error in epicenter and depth determinations (in kilometers)*.

Q SQD: Indicates solution quality of the hypocenter. The first column of letters A, B, C, or D is a measure intended to indicate the general reliability of the solution:

Q	Epicenter	Focal Depth
A	excellent	good
B	good	fair
C	fair	poor
D	poor	poor

Q is taken as the average of QS and QD (defined below). For example, an A and a C yield a B, and two B's yield a B. When S and QD are only one level apart, the lower one is used, i.e., and A and a B yield a B.

S, the second column, is rated by the statistical measure of the solution as follows:

S	RMS (Sec)	ERH (KM)	ERZ (KM)
A	0.15	1.0	2.0
B	0.30	2.5	5.0
C	0.50	0.50	
D	Others		

*Statistical interpretation of standard errors involves assumptions which may not be met in earthquake locations. Therefore, the standard errors may not represent actual error limits.

QD, the third column, is rated according to the station distribution as follows:

QD	NO	GAP	DMIN
A	6	90°	Depth or 5 km
B	6	135°	2x depth or 10 km
C	6	180°	50 km
D	Others		

Where NO is the number of seismographic stations in the determination, GAP is the largest azimuthal separation in degrees between stations, DMIN is the epicentral distance to the nearest station. The values for NO, GAP and DMIN are not shown in Table I.

TABLE I

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	RMS	ERH	ERZ	Q	SRC
750829	0419	03.44	39 26.66	121 32.21	0.02	3.5	0.00	0.7	0.0	B A B
750829	0443	29.06	39 27.01	121 32.41	0.47	2.0	0.10	2.0	3.4	C C B
750829	1414	19.22	39 26.23	121 32.39		2.6	0.24			C
750706	0411	02.36	39 27.66	121 32.11	4.09	2.2	0.02	0.2	0.4	B A C
750706	1321	09.65	39 27.91	121 34.96		2.0	0.31	2.0		C
750728	0928	09.95	39 27.69	121 32.43	0.56	2.6	0.03	0.9	0.0	B A B
750728	1030	02.36	39 27.12	121 33.87	5.67	2.1	0.01	0.2	0.2	B A B
750721	0417	37.37	39 26.20	121 31.49	7.56	2.9	0.10	3.2	3.5	C C C
750801	1949	37.62	39 27.20	121 32.50	7.07	3.0	0.00	0.0	0.0	B A C
750801	1027	17.61	39 26.39	121 33.01	5.01	4.7	0.10	1.0	1.1	C B C
750801	1726	49.92	39 27.76	121 32.69	0.58	3.0	0.09	0.6	0.8	B A B
750801	1817	22.92	39 26.39	121 34.79		2.2	0.07	1.5		B
750801	1938	42.74	39 25.53	121 33.42		2.6	0.16	2.2		B
750801	2020	04.52	39 26.01	121 32.16	0.01	4.9	0.12	0.8	0.7	B A B
750801	2020		39 26.01	121 32.18	0.01	5.7				
750801	2029		39 26.01	121 32.16	0.01	4.7				
750801	2029		39 26.01	121 32.16	0.01	4.8				
750801	2032	39.01	39 26.99	121 34.79	0.71	3.8	0.08	0.4	0.5	B A B
750801	2037		39 26.99	121 34.76	0.71	3.5				
750801	2040	20.24	39 26.01	121 32.52	0.76	2.5	0.11	1.3	1.2	B B B
750801	2041	41.38	39 26.68	121 31.06	4.42	2.5	0.33	3.2	2.8	C C B
750801	2043	23.13	39 26.02	121 29.87	4.43	2.5	0.13	1.1	1.0	C B C
750801	2048	10.16	39 27.78	121 34.07	7.23	3.0	0.00	0.0	0.0	B A B
750801	2048		39 27.76	121 34.07	7.23	3.0				
750801	2054	56.96	39 25.44	121 32.43		2.5	0.23	3.4		C
750801	2102	03.27	39 27.02	121 33.64		2.0	0.14	1.2		B
750801	2105	39.78	39 26.02	121 34.07	0.48	3.0	0.04	0.3	0.3	B A B
750801	2109	56.46	39 26.67	121 32.92	0.10	2.6	0.02	0.3	0.3	B A B
750801	2110	15.89	39 26.99	121 34.96	7.02	2.0	0.00	0.0	0.0	B A B
750801	2110	23.61	39 26.36	121 32.47	0.14	2.0	0.06	0.7	0.0	B A B
750801	2120	07.56	39 26.17	121 34.56	0.13	2.0	0.07	0.0	0.7	B A B
750801	2121	06.92	39 27.10	121 32.66	7.00	4.1	0.05	0.3	0.2	B A B
750801	2128	06.02	39 26.77	121 31.76	7.67	3.3	0.04	0.3	0.2	B A B
750801	2129	22.96	39 27.60	121 33.29	7.29	3.0	0.09	0.7	0.7	B A B
750801	2139	59.38	39 27.20	121 32.10	7.79	2.7	0.10	0.0	0.9	B A B
750801	2150	14.13	39 26.11	121 34.74	6.76	2.0	0.13	1.4	1.5	B B B
750801	2204	58.77	39 26.04	121 31.39	7.54	2.9	0.07	0.9	0.4	B A B
750801	2209	00.10	39 25.46	121 34.96	7.92	2.5	0.06	0.6	0.8	B A B
750801	2211	04.54	39 27.09	121 34.27	7.97	2.9	0.23	1.4	1.4	B B B
750801	2223	42.89	39 25.94	121 32.21	6.65	2.9	0.17	1.8	1.6	C B C
750801	2224	04.42	39 26.16	121 34.48	7.22	2.5	0.07	0.9	0.7	B A B
750801	2230	20.21	39 26.16	121 34.21	0.91	2.7	0.17	1.7	1.8	C B C
750801	2232	56.89	39 26.13	121 33.68	0.11	2.8	0.30	3.1	2.8	C C B
750801	2235	40.23	39 31.17	121 34.29		2.5				D
750801	2304	12.62	39 27.79	121 34.21	0.91	2.5	0.16	1.8	1.5	B B B
750801	2310	43.66	39 26.36	121 33.68		2.5	0.20	4.5		C
750801	2331	32.61	39 26.78	121 32.44	6.22	2.5	0.19	1.9	1.9	B B B
750801	2344	48.75	39 29.48	121 31.98	7.01	3.2	0.08	0.4	0.3	A A A
750801	2350	53.26	39 26.68	121 33.96		2.4	0.07	1.4		B
750801	2351	48.78	39 25.45	121 34.92		2.2	0.33	5.8		D
750802	0042	44.76	39 25.16	121 28.74	5.68	2.5	0.15	1.8	2.6	C B C
750802	0049	59.76	39 25.13	121 31.68		2.3	0.24	4.8		C
750802	0413	28.84	39 26.82	121 34.74		2.6	0.19	3.9		C
750802	0439	04.88	39 26.81	121 34.69	0.11	2.8	0.22	2.2	2.9	C B C
750802	0452	46.22	39 36.38	121 31.79	0.49	3.8	0.11	0.8	0.7	A A A
750802	0458	55.79	39 26.42	121 32.98	0.14	2.8	0.21	2.7	2.6	C C B
750802	0131					2.3				
750802	0144	12.43	39 29.66	121 31.72	0.91	2.2	0.05	0.5	0.5	B A B
750802	0227	04.66	39 26.26	121 34.28	7.92	2.6	0.07	0.8	0.8	B A B

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	RMS	ERH	ERZ	Q	SRC
750802	0315	26.99	39 26.23	121 26.36		2.8	0.28	0.1		D
750802	0443	35.39	39 26.23	121 26.98		2.7	0.09	1.6		B
750802	0448	29.26	39 26.12	121 34.21	7.75	3.1	0.07	0.8	0.7	B A B
750802	0831	06.92	39 26.86	121 34.13	5.74	3.2	0.06	0.8	0.7	B A C
750802	1007	58.06	39 27.46	121 32.76	9.14	2.8	0.05	0.4	0.8	B A B
750802	1011	53.81	39 29.74	121 31.46	7.03	2.1	0.06	0.4	0.3	A A A
750802	1048	56.96	39 26.52	121 29.89	5.98	3.3	0.03	0.3	0.4	B A C
750802	1151	56.56	39 29.11	121 34.44	4.81	3.4	0.02	0.1	0.2	B A B
750802	1442					2.4				
750802	1444	26.87	39 29.45	121 34.18	6.34	2.1	0.08	0.4	0.4	B A C
750802	1651	44.96	39 28.60	121 29.97	7.36	3.7	0.00	0.0	0.6	B A B
750802	1724	29.09	39 28.96	121 29.37	6.66	4.3	0.10	0.7	0.6	B A B
750802	1743	23.96	39 29.02	121 29.48	6.64	4.8	0.11	0.7	0.7	B A B
750802	1912	58.24	39 28.72	121 34.07	8.27	2.8	0.03	0.2	0.3	B A B
750802	1958	26.66	39 27.21	121 32.77	7.72	3.1	0.04	0.3	0.2	B A B
750802	2022	16.22	39 27.68	121 29.83	9.89	3.1	0.12	0.8	0.9	B A B
750802	2036					2.4				
750802	2039	40.47	39 28.83	121 29.76	8.28	3.9	0.10	0.7	0.7	B A B
750802	2050	55.56	39 28.82	121 29.24	8.92	3.8	0.11	0.9	0.8	B A B
750802	2059		39 28.82	121 29.24	8.92	3.2				
750802	2111	44.34	39 27.64	121 29.68	9.81	2.8	0.07	0.6	0.7	B A B
750802	2140	01.22	39 28.66	121 29.44	8.61	3.9	0.07	0.8	0.9	B A C
750802	2235					2.9				
750803	0103	08.56	39 29.82	121 31.72	8.49	4.8	0.04	0.3	0.2	A A A
750802	0140					2.4				
750803	0207	08.41	39 29.54	121 34.03	7.29	4.1	0.05	0.2	0.2	B A B
750803	1902	10.01	39 29.14	121 34.58	6.07	2.8	0.05	0.9	4.8	B A C
750802	1647	46.05	39 28.19	121 29.46	9.12	2.4	0.09	0.7	0.9	B A B
750802	1747	59.43	39 29.87	121 29.96	6.66	2.5	0.13	1.1	1.2	B B B
750803	2036	29.21	39 27.83	121 29.58	9.73	2.8	0.04	0.5	0.5	B A B
750803	2349	03.42	39 29.96	121 31.17	7.27	2.8	0.07	0.6	0.6	A A A
750804	0343	04.06	39 28.57	121 28.72	6.99	2.8	0.09	0.8	1.8	B A C
750804	0947	44.79	39 25.24	121 31.01	7.46	3.5	0.04	0.5	0.5	B A C
750804	1719	28.13	39 23.86	121 21.26		2.7	0.09	2.7		C
750805	0220	07.62	39 24.81	121 29.99	0.01	3.3	0.25	1.7	1.7	C B C
750805	0913	24.03	39 28.56	121 31.17	0.93	2.5	0.23	2.4	2.1	B B B
750805	2044	29.19	39 24.66	121 31.07	4.78	3.2	0.17	1.1	1.2	C B C
750805	2357					2.5				
750806	0350	29.63	39 29.52	121 32.36	0.04	4.7	0.15	0.8	0.7	A A A
750806	0440	48.13	39 28.23	121 34.07	0.64	2.8	0.18	1.4	1.5	C B C
750806	0438					2.4				
750806	0949	32.81	39 29.55	121 32.99	7.48	2.7	0.22	3.1	3.7	C C B
750806	1342	28.39	39 30.66	121 33.01	0.44	2.9	0.26	1.6	1.3	B B A
750806	1349	30.93	39 28.43	121 32.47	7.39	2.4	0.23	2.1	3.4	C C B
750806	1625	47.34	39 29.30	121 29.81	9.83	3.1	0.13	1.0	1.2	C B C
750806	1841	21.04	39 29.81	121 32.76	0.24	3.6	0.09	0.7	0.6	A A A
750806	1942	40.34	39 30.25	121 32.59	7.76	2.8	0.12	1.1	1.2	B B B
750806	2140	32.07	39 25.63	121 31.87	6.95	3.8	0.11	0.8	0.9	B A C
750806	2140		39 25.63	121 31.87	6.55	3.8				
750807	0519	40.86	39 24.89	121 28.76		2.3	0.21	4.7		C
750807	1420	45.19	39 30.96	121 32.98	7.58	2.9	0.24	1.4	1.2	B B A
750807	1912	55.63	39 30.78	121 32.48	0.21	2.8	0.06	0.5	0.5	B A B
750807	2015	39.53	39 25.27	121 29.25	5.23	2.8	0.18	1.2	1.8	C B C
750807	2031	28.13	39 26.76	121 32.92	7.41	3.1	0.25	1.9	1.3	B B A
750808	0718	49.92	39 29.96	121 32.12	7.78	4.9	0.17	1.0	0.9	B B A
750808	1337	53.48	39 29.92	121 30.42	6.71	3.2	0.04	0.2	0.3	A A A
750808	1558	08.33	39 28.49	121 29.67	7.29	2.6	0.29	0.8	1.1	B A B
750808	1903	27.28	39 24.75	121 29.98	7.28	3.1	0.08	0.4	0.4	B A C
750809	0738	47.26	39 24.81	121 30.39	7.21	3.4	0.18	0.8	0.7	B A B
750809	1145					2.4				

TABLE 1 (con't)

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	RMS	ERH	ERZ	Q	SOU
790000	1211				2.4					
790009	2049	31.00	39 25.11	121 29.46	4.49	2.8	0.13	1.1	1.7	B B B
790010	1113				2.4					
790011	0240	16.94	39 28.31	121 28.54	5.89	3.6	0.10	0.7	0.8	B A B
790011	0411	36.33	39 27.89	121 29.40	5.56	4.3	0.11	0.7	0.7	B A B
790011	0634	58.92	39 25.78	121 31.31	4.71	2.8	0.06	0.6	0.9	B A B
790011	0741	38.89	39 25.42	121 30.16	6.39	2.7	0.09	0.8	1.1	B A B
790011	1959	59.32	39 29.75	121 32.42	0.14	3.6	0.14	0.9	0.8	A A A
790012	0429	02.20	39 27.68	121 30.32	6.49	2.8	0.11	0.8	0.9	A A A
790012	1150	31.05	39 28.47	121 33.89	6.84	3.8	0.10	1.9	1.9	B B B
790012	1642	08.86	39 31.93	121 32.48	8.31	2.9	0.27	1.9	2.6	B B B
790012	1948	12.82	39 26.86	121 31.83	7.49	2.7	0.10	0.8	1.8	B A B
790016	0548	09.17	39 28.40	121 32.65	0.82	4.8	0.06	0.4	0.3	A A A
790016	1449	29.73	39 29.73	121 30.83	6.73	2.8	0.06	0.4	0.4	A A A
790016	1223	24.25	39 30.88	121 31.13	6.99	3.2	0.13	1.8	0.9	A A A
790016	1446	58.39	39 29.78	121 30.49	6.75	2.8	0.05	0.3	0.3	A A A
790018	0356	53.15	39 25.88	121 30.88	0.86	3.8	0.18	0.8	0.8	A A A
790018	0711	42.44	39 25.46	121 30.43	7.48	2.8	0.18	1.5	1.5	B B B
790020	0230	16.38	39 25.91	121 30.67	0.41	3.8	0.09	0.8	1.8	B A B
790021	1948	38.89	39 26.86	121 28.77	0.48	2.8	0.03	0.5	0.8	B A B
790023	1631	32.99	39 29.88	121 30.15	0.41	2.8	0.09	0.3	0.3	A A A
790024	0918	37.42	39 30.89	121 30.34	0.81	3.1	0.06	0.6	0.3	A A A
790025	1335	11.28	39 30.45	121 30.29	0.29	3.3	0.04	0.2	0.2	A A A
790026	1827	43.86	39 26.34	121 30.44	7.72	2.7	0.41	3.3	4.2	C C B
790029	0949	31.82	39 28.74	121 31.84	7.82	2.9	0.04	0.3	0.4	B A B
790029	0948	13.17	39 31.84	121 32.76	7.96	3.8	0.22	2.8	2.1	B B B
790029	1446	28.96	39 30.91	121 32.66	0.87	3.8	0.16	1.7	1.4	B B B
790031	0432	14.49	39 25.31	121 30.67	0.46	2.6	0.03	0.2	0.3	B A B
790903	2126	53.97	39 28.66	121 30.62		2.2	0.48	8.2		D
790904	0117	01.07	39 24.29	121 34.29	0.36	3.8	0.11	1.2	1.9	C B C
790904	1939	25.38	39 29.96	121 33.96	5.88	3.1	0.16	2.4	3.3	B B B
790904	1643	43.94	39 25.72	121 30.16	7.87	2.8	0.04	1.8	1.3	B A B
790905	2141	39.85	39 25.15	121 32.23	7.19	3.8	0.23	1.7	1.5	C B C
790906	0137	05.19	39 24.03	121 31.59	6.85	2.9	0.21	2.2	2.3	C B C
790906	0942	38.16	39 27.81	121 31.16	9.16	2.9	0.07	1.8	1.1	B B A
790907	1847	18.66	39 28.82	121 28.63		2.8	0.14	9.8		D
790910	1238	36.35	39 30.28	121 34.37		3.2	0.19	3.2		C
790910	1723	46.82	39 30.10	121 34.93		2.9	0.21	3.5		C
790910	1739	04.09	39 31.76	121 35.32	4.74	3.4	0.15	1.3	1.6	B B B
790910	1858	39.44	39 30.43	121 34.41		2.3	0.23	3.8		C
790912	0240	47.78	39 30.83	121 30.89		3.1	0.18	2.8		B
790920	0693	41.01	39 30.19	121 32.97		2.8	0.21	2.8		B
790922	2125	9.13	39 27.93	121 31.34	8.18	2.4	0.19	1.6	1.4	B B B
790923	1346	23.09	39 25.91	121 30.92	4.58	2.8	0.04	0.9	0.9	C A D
790926	0231	07.19	39 30.92	121 33.48	9.76	4.8	0.39	3.4	2.3	C C B
790926	0439	52.74	39 25.89	121 32.94	6.94	2.8	0.09	1.9	1.3	C B C
790926	0857	16.11	39 26.74	121 31.23	9.94	2.9	0.31	3.1	2.1	C C B
790927	0247	10.54	39 29.78	121 31.91	9.27	2.1	0.16	4.3	4.5	D C D
790927	1349	14.90	39 30.89	121 32.49		2.3	0.12	3.1		C
790927	2254	37.99	39 30.40	121 30.62	5.03	4.6	0.88	8.1	1.7	B B B
790927	2248	14.04	39 31.00	121 34.48	4.89	2.9	0.09	0.8	0.8	B A C
790927	2304	36.96	39 30.02	121 33.34	9.48	3.4	0.36	2.8	2.8	C C B
790927	2328	04.71	39 30.69	121 31.93	9.89	3.2	0.06	0.4	0.5	B A B
790927	2338	08.36	39 30.99	121 34.60	5.99	2.6	0.12	1.2	1.1	C B C
790928	0428	19.94	39 31.64	121 34.49	3.74	2.8	0.13	2.8	2.8	C B D
790928	0949	02.87	39 30.18	121 32.89	0.43	1.7	0.07	0.9	0.9	B A B
790928	2107	14.35	39 31.57	121 32.94	9.11	3.3	0.23	1.7	1.4	B B B
790928	0925	37.69	39 24.65	121 32.37		2.2	0.41	2.8		C
790929	0243	36.20	39 26.96	121 31.82	2.26	2.4	0.18	1.1	1.3	C B C
790930	2230	04.40	39 31.86	121 33.82	9.18	2.1	0.17	1.7	1.9	C B C

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	RMS	ERH	ERZ	Q	SOU
791002	2142	29.51	39 27.21	121 30.27		2.8	0.13	9.4		D
791002	2219	0.03	39 26.73	121 29.67		2.8	0.21	1.9		B
791002	2230	28.39	39 27.49	121 31.81		2.8	0.36	4.8		C
791003	0311	29.33	39 24.29	121 35.99	4.24	1.8	0.11	1.9	2.9	C B C
791004	0819	18.64	39 24.31	121 32.43		2.6	0.13	2.2		B
791004	1229	39.78	39 29.95	121 33.41		2.8	0.19	3.3		C
791010	0744	47.97	39 27.94	121 30.67	4.79	3.5	0.07	0.7	0.6	B A B
791012	2324	17.44	39 25.24	121 32.64	6.39	1.4	0.08	1.2	1.5	C B C
791013	1456	37.05	39 29.95	121 31.56	4.28	2.8	0.10	1.3	1.2	B B A
791013	1646	51.23	39 29.98	121 32.13	4.75	3.4	0.10	1.4	1.3	B B B
791018	1559	42.69	39 24.36	121 33.36		1.3	0.12	2.4		B
791027	2142	44.24	39 30.94	121 32.46	3.42	2.7	0.29	2.8	2.3	B B B
791028	0341	15.86	39 29.82	121 31.37	5.11	3.3	0.23	1.4	1.3	B B B
791028	0913	46.05	39 31.92	121 33.15	6.18	1.8	0.28	1.4	1.5	B B B
791030	1409	19.61	39 28.99	121 29.83	5.37	1.8	0.01	0.3	0.3	C A D
791103	1913	37.19	39 24.23	121 32.36		2.8	0.27	6.4		D
791103	0937	46.75	39 24.47	121 31.63	4.44	3.3	0.12	1.3	1.5	C B C
791107	2358	42.49	39 29.26	121 31.66	3.92	2.3	0.09	0.8	1.8	B A C
791108	0444	08.87	39 29.63	121 29.93	2.36	2.8	0.18	1.1	1.8	B B B
791110	0436	54.72	39 24.39	121 30.77		1.8	0.07	0.7		A
791113	1146	03.23	39 27.19	121 28.28		1.6	0.28	2.1		C
791119	0338	01.75	39 25.64	121 30.25	0.43	4.3	0.16	1.8	0.9	B B B
791119	0345	03.25	39 25.93	121 30.84	4.18	2.1	0.14	0.9	1.2	B A C
791119	1341	16.92	39 24.69	121 30.84	2.19	1.8	0.10	0.8	1.8	B A B
791116	1917	14.39	39 25.82	121 31.28	2.58	2.2	0.16	1.8	1.6	B B B
791118	1316	42.95	39 27.95	121 27.83		2.4	0.11	0.8		A
791120	1234	19.10	39 25.82	121 28.62		1.7	0.10	1.1		B
791123	0732	53.67	39 24.88	121 30.84	2.56	2.1	0.19	0.9	1.1	B A B
791123	2142	07.20	39 24.11	121 28.68	3.67	1.8	0.52	4.2		D
791124	0941	40.25	39 25.57	121 32.11		1.7	0.14	2.1		C
791126	1251	55.33	39 24.98	121 29.34		2.4	0.10	0.8		A
791127	2399	28.88	39 25.71	121 31.72		1.5	0.19	2.4		C
791130	1023	28.94	39 30.98	121 29.45		2.1	0.21	1.1		B
791203	0712	13.14	39 25.73	121 29.82	3.82	2.5	0.16	1.5	1.9	C B C
791205	1825	42.39	39 25.13	121 28.93	3.88	2.0	0.06	0.7	1.2	B A C
791210	0340	40.36	39 30.38	121 33.16	5.74	2.8	0.14	1.2	1.6	B B B
791213	0254	43.42	39 27.89	121 30.84	2.35	2.1	0.03	0.3	0.5	B A C
760101	1858	39.31	39 25.33	121 29.36		2.1	.14	1.3		B
760103	1438	38.84	39 26.85	121 30.49		1.9	.18	1.8		A
760104	1941	38.81	39 30.64	121 32.17		1.7	.22	2.7		C
760109	1754	26.81	39 29.22	121 28.93		2.1	.16	1.2		B
760110	2331	48.31	39 30.96	121 28.22		1.9	.11	0.6		C
760117	0719	19.89	39 25.86	121 29.86	4.73	2.8	.03	1.2	1.2	B B B
760118	0837	23.88	39 24.95	121 29.82	5.26	2.9	.29	1.4	1.3	B B B
760120	0201	42.37	39 29.14	121 28.96	3.89	2.5	.26	1.6	1.9	B B B
760120	1948	80.78	39 24.94	121 28.48	4.65	3.8	.22	1.4	1.9	B B B
760120	0952	19.47	39 24.27	121 29.71		2.3	.13	0.8		A
760120	2341	34.93	39 23.98	121 29.78	6.84	2.3	.18	0.9	1.8	B A B
760202	1911	50.44	39 28.82	121 29.16	5.25	1.7	.03	0.7	1.3	A
760205	0811	53.89	39 24.38	121 28.28	4.44	.8	.01	0.2	0.3	A
760208	1257	46.82	39 31.46	121 31.21	9.71	0.9	.06	0.3	0.7	B A B
760804	0949	10.87	39 30.21	121 29.38	4.26	0.4	.01	0.1	0.2	A
760209	0956	47.89	39 29.85	121 28.94		1.5	.24	0.8		C
760209	1140	46.61	39 29.84	121 29.65		1.8	.13	0.8		A
760209	1333	03.78	39 30.11	121 31.88	5.29	2.5	.25	1.7	2.8	B B B
760209	1342	39.85	39 29.46	121 28.38		1.6	.12	0.5		B
760209	1397	09.88	39 28.84	121 31.53	4.91	1.9	.37	2.3	2.6	C C B
760810	0934	10.96	39 29.87	121 28.82	4.65	0.2	.01	0.3	0.5	C
760810	0118	03.86	39 25.26	121 27.82	2.91	0.1	.13	0.3	0.8	A
760819	0143	09.81	39 29.67	121 28.61	5.89	1.4	.08	0.5	1.8	A

TABLE 1 (con't.)

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	RMS	ERH	ERZ	Q	SRO
760219	1214 44.73	39 28.37	121 31.22	6.86	5.2	.01	5.4	6.7	A	
760222	1738 35.32	39 28.15	121 31.65	4.51	6.1	.02	5.7	1.8	A	
760220	0741 55.84	39 26.68	121 31.94	7.96	5.1	.15	5.6	1.6	A	
760306	0618 38.96	39 26.63	121 28.99	4.44	6.6	.05	5.4	1.5	A	
760313	5607 44.84	39 25.41	121 31.32	5.68	6.2	.13	5.7	1.9	A	
760214	0045 22.41	39 31.59	121 31.29	6.95	5.1	.05	5.7	6.6	A	
760314	5048 05.66	39 25.34	121 35.96	7.30	6.3	.50	6.5	6.9	A	
760313	5045 19.32	39 24.36	121 28.43	6.68	6.6	.05	5.1	6.1	A	
760315	6714 15.99	39 24.15	121 29.34	6.28	2.9	.50	5.5	6.6	A	
760318	5754 35.67	39 23.89	121 29.79	7.62	6.6	.05	5.1	6.1	A	
760316	5242 34.83	39 26.12	121 29.93	3.21	6.6	.02	6.3	6.7	A	
760319	6614 15.23	39 27.13	121 30.34	3.95	5.1	.51	5.1	6.2	A	
760315	1625 68.85	39 32.66	121 30.98	7.59	6.6	.02	5.3	6.3	A	
760319	5214 06.31	39 32.37	121 30.52	5.67	1.7	.23	5.5	1.5	B	
760326	5543 66.52	39 24.37	121 29.68	9.86	6.8	.61	5.5	6.2	A	
760326	1157 13.86	39 26.93	121 31.69		6.6	.15			A	
760326	1249 42.16	39 24.81	121 28.16		2.5	.13	5.6		A	
760326	2314 39.67	39 24.23	121 25.35	6.16	5.1	.07	6.6	1.5	A	
760322	5299 36.66	39 25.87	121 31.81	6.96	6.1	.65	6.6	6.5	A	
760322	2045 28.10	39 24.72	121 31.62	6.35	6.1	.09	1.6	6.5	A	
760327	1551 42.69	39 29.95	121 28.87		2.5	.59	6.5		A	
760328	5802 58.71	39 29.62	121 30.66	7.01	2.2	.13	1.6	6.8	S	
760326	5103 50.96	39 26.52	121 29.22	6.96	6.3	.05	5.6	6.7	A	
760331	2050 32.45	39 29.95	121 31.66	7.03	6.5	.09	6.7	1.2	A	
760401	2303 69.36	39 26.75	121 30.69	6.98	6.3	6.12	6.5	1.6	S	A S
760404	1506 31.77	39 26.61	121 28.06		2.2	6.23	1.2		B	
760405	5061 22.96	39 29.67	121 30.23	6.98	1.2	6.12	5.5	1.2	B	A C
760412	1757 21.66	39 26.55	121 29.61	5.62	6.3	6.55	6.9	6.5	S	A C
760413	1906 21.36	39 23.59	121 31.98	5.56	6.2	6.66	6.6	1.3	S	A C
760416	0625 29.78	39 25.66	121 29.26	2.65	<.6	6.61	6.1	6.2	A	A
760416	1305 59.56	39 29.56	121 29.59	6.33	6.6	5.11	6.5	1.6	S	A B
760416	1711 56.76	39 29.65	121 29.23	1.33	3.6	5.15	5.7	1.7	B	A B
760415	1817 62.79	39 29.96	121 30.56	6.96	<.6	6.61	6.2	6.2	B	A C
760422	6706 57.73	39 32.22	121 35.51	5.61	6.6	6.62	6.3	6.3	A	
760422	1335 36.76	39 24.78	121 29.67	5.59	6.1	6.56	1.5	1.6	B	
760423	6291 66.28	39 31.16	121 31.66	19.66	6.3	6.15	1.6	6.8	S	
760428	5266 63.22	39 26.66	121 28.61	2.96	6.3	6.12	5.5	1.8	B	A C
760426	6349 29.37	39 26.66	121 29.72	5.62	6.6	6.66	6.5	6.8	B	A S
760427	6226 12.52	39 23.69	121 27.96	6.12	<.6	6.15	6.9	2.5	B	A C
760436	5667 26.66	39 31.58	121 29.26	5.61	6.6	6.62	5.3	6.6	B	A C
760436	6765 56.76	39 25.66	121 28.22	6.23	6.2	6.65	6.6	1.6	B	A C
760436	2651 39.19	39 25.96	121 29.16		2.1	5.16	6.6		A	

TABLE II

	EARTHQUAKE	b-VALUE	RESERVOIR	REFERENCE*
KARIBA:	Foreshocks	1.1	yes	Gough and Gough (1970a, b)
	Aftershocks w/o mainshock	1.0	"	" " "
	Regional	0.8	"	Gupta, et al (1972b) Africa
KREMASTA:	Foreshocks	1.4	yes	Comninakis, et al (1968)
	Aftershocks w/o mainshock	1.1	"	" " "
	Aftershocks with mainshock	0.9	"	Morrison, Stump & Uhrhammer (1976)
	Regional	0.8	"	Galanopoulos (1967) Greece
KOYNA:	Foreshocks	1.9	yes	Gupta, et al (1972b)
	Aftershocks w/o mainshock	1.3	"	" " "
	Regional	0.5	"	" " peninsular India
OROVILLE:	Foreshocks	0.37	yes	Morrison, Stump & Uhrhammer (1976)
	Aftershocks with mainshock	0.61	"	" " "
	Aftershocks w/o mainshock	0.61	"	" " "
	Regional (1962-1969)	0.78	no	Bolt and Miller (1971)
CORRALITOS:	Aftershocks w/o mainshock	0.63	no	McEvilly (1966)
COALINGA:	Aftershocks with mainshock	0.58	no	Morrison, Stump & Uhrhammer (1976)
	Aftershocks w/o mainshock	0.66	no	" " "
PARKFIELD:	Aftershocks with mainshock	0.63	no	McEvilly, et al (1967)
SAN FERNANDO:	Aftershocks with mainshock	0.64	no	Bolt and Gopalakrishnan (1975)
	Aftershocks w/o mainshock	1.01	no	" "
	Regional (1932-1971)	0.98	no	Seismicity of Southern California, Cal. Tech. 1973
KERN COUNTY:	Aftershocks with mainshock	0.70	no	Morrison, Stump & Uhrhammer (1976)
	Aftershocks w/o mainshock	0.96	no	" " "

*See Bibliography

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